ADAPTIVE TECHNIQUE FOR ENERGY MANAGEMENT IN WIRELESS SENSOR NETWORKS

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ADAPTIVE TECHNIQUE FOR ENERGY MANAGEMENT IN WIRELESS SENSOR NETWORKS

Development, Simulation and Evaluation of Adaptive Techniques for Energy Efficient Routing Protocols Applied to Cluster Based Wireless Sensor Networks

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This thesis is dedicated to the memory of my aunt

Fatima H. Ghneimat

Who passed away just two days after defending this thesis

Abstract

Recently, wireless sensor networks have become one of the most exciting areas for research and development. However, sensor nodes are battery operated, thus the sensor's ability to perform its assigned tasks is limited by its battery capacity; therefore, energy efficiency is considered to be a key issue in designing WSN applications.

Clustering has emerged as a useful mechanism for trade-off between certain design goal conflicts; the network life time, and the amount of data obtained. However, different sources of energy waste still exist. Furthermore, in such dynamic environments, different data rate requirements emerge due to the current network status, thus adapting a response to the changing network is essential, rather than following the same principle during the network's lifespan.

This thesis presents dynamic techniques to adapt to network changes, through which the limited critical energy source can be wisely managed so that the WSN application can achieve its intended design goals. Two approaches have been taken to decreasing the energy use. The first approach is to develop two dynamic round time controllers, called the minimum round time controller MIN-RC and the variable round time controller VAR-RC, whereas the second approach improves intra-cluster communication using a Co-Cluster head; both approaches show better energy utilisation compared to traditional protocols. A third approach has been to develop a general hybrid protocol H-RC that can adapt different applications requirements; it can also tolerate different data rate requirements for the same application during the system's lifetime.

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Publications

1. A.Ghneimat, J. Mellor, and J. Ping, "*Adaptive, Cluster Based, Sensor Network Routing Protocol*," in Computer Modelling and Simulation (UKSim), 2011 UkSim 13th International Conference on, 2011, Cambridge UK, pp. 472-476.

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3. A.Ghneimat, J. Mellor, and J. Ping, " *Cluster Head Optimization for Wireless Sensor Networks*" in Proceedings of 27th Annual UK Performance Engineering Workshop (UKPEW 2011), Bradford, UK 2011, pp 252-260.

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List of Abbreviations

ADC	Analog To Digital Converter ADC
AODV	Ad hoc On-Demand Distance Vector
APTEEN	Adaptive Periodic Threshold-sensitive Energy Efficient Sensor Network Protocol
BCDCP	Base-Station Controlled Dynamic Clustering Protocol
B-MAC	Berkeley Media Access Control
CPCP	Coverage-Preserving Clustering Protocol
CSMA	Carrier Sense Multiple Access
DSDV	Destination-Sequenced Distance-Vector Routing protocol
DSP	Digital Signal Processing
GAF	Geographic Adaptive Fidelity
GEAR	Geographical and Energy Aware Routing
HEED	Hybrid Energy-Efficient Distributed Clustering
ISM	Industrial Scientific And Medical
LEACH	Low-Energy Adaptive Clustering Hierarchy
LEACH-C	Centralised LEACH
MAC	Medium Access Control
MANET	Mobile Ad-Hoc Network
MMSPEED	Multi-path and Multi-SPEED
PEGASIS	Power-Efficient Gathering in Sensor Information Systems
QoS	Quality Of Service
SAR	Sequential Assignment Routing
SMAC	Sensor MAC

SPEED	Stateless Protocol for Real-Time Communication In Sensor Networks
SPIN	Sensor Protocols for Information via Negotiation
TDMA	Time Division Multiple Access
TEEN	Threshold sensitive Energy Efficient sensor Network protocol
TMAC	Time-Out MAC
VR-LEACH	Variable LEACH
WSN	Wireless Sensor Networks
Z-MAC	Zebra MAC

CHAPTER 1

Introduction

1.1 Introduction

The recent advancements in wireless communications and electronics has led to the development of low-cost, low-power, multifunctional small smart sensors. These sensors should have the ability to sense, process data, and communicate with each other via a wireless connection. a wireless sensor network is an infrastructure comprised of number of spatially distributed autonomous wireless sensors nodes to monitor a phenomenon in a specified environment, and to cooperatively forward their measures(collected data) through the network to a desired sink(s)[1] [2].

1.2 Sensor Networks

Deployment of large number of these battery operated nodes can be carried out to measure environmental factors such as light, temperature, humidity, and to report the collected data via a wireless connection to an intended application where it could be processed. This could be implemented in policy-making to improve people's lives by increasing efficiency, productivity, protection and safety[3]. Recently, wireless sensor networks have found their way into a wide variety of applications and systems, despite the large variation in these applications' requirements. This therefore opens the door for new research[4].

The typical applications of WSN are, but not limited to: disaster relief, emergency rescue operations, military, habitat monitoring and environmental monitoring[5, 6], agriculture[7, 8], health care[9], home automation[10-13], industrial and manufacturing automation[14], and physical security. Moreover this will give WSN the ability to be a key principle in causing computers to anticipate our needs and, if necessary, act on our behalf[3]. There is great diversity in these applications considering the special characteristics and requirements of each type of these applications; for example, monitoring the climate for a specific application where periodic sampling is required, or the sampled data could be stored and processed locally by the node before forwarding it, while in other applications, two-way interaction required where the nodes should react to answer the sink's queries.

1.3 Characteristics and Design Issues in WSN

The design of the wireless sensor network is influenced by many issues. Some of these issues have been addressed in[15], such as the wide variety of WSN applications, network size; the limited computational capabilities and limited power of the sensor nodes; however, sensor networks may consist of various types of nodes, with different communications and computations capabilities, also some nodes may be equipped with higher energy[15], moreover node heterogeneity can have the advantage to improve the network efficiency [16-18], the production costs; the random deployment of these sensor nodes over the sensing field to perform sensing, and processing and data dissemination to the sink.

1.3.1. Some of the Design issues and Challenges[4, 15]:

Fault Tolerance: sensor nodes are usually scattered over inaccessible harsh areas, and a sensor node may fail due to battery depletion, physical damage or hardware problems. It is expected that the number of failure nodes will be higher in WSN than wired networks, so the routing protocol should report these failed nodes and respond to this failure by finding an alternate path to forward data to the sink.

Scalability : the large number of densely deployed sensors in wireless sensor networks means a sensor node may have several tens, hundreds or more neighbours, and each of these nodes performs sensing and transmitting data, which raises the ratio of transmissions in the sensor's transmission range; therefore, the protocols should be scalable to ensure the adequate performance of the network.

Production Costs: The cost of a sensor node is critical in justifying the cost of the whole network, assuming that the network consists of a large number of disposable nodes. As a result, the production cost of each node should be low.

Hardware Constraints: The primary components of the sensor nodes are: the sensing unit (sensor and ADC), processing unit, transmission unit and power unit. All of these components should fit in a small sized-module- maybe match-box size or smaller. However, other components could be added depending on the application's requirements, such as mobilisation and localisation systems. In addition to size constraints, each added component will increase the cost of the sensor and of course consumes more energy.

Transmission Media: most sensors communicate using radio communications over ISM bands, while other sensors use infrared or optical communications. Using optical and infrared communication is more robust and virtually interference free.

Power Consumption: Energy consumption is considered to be the biggest challenge in designing wireless sensor networks. The battery size is limited by the node's size. The sensor's main task is to sense, process sensed data, and transmit the data to the sink, so the main energy consumption is, processing and communication; thus, the software and hardware components should be carefully designed whilst considering the power limitations.

Deployment: A sensor can be manually deployed by placing nodes one by one over the sensing field or usually by scattering in a random manner over the sensing field (e.g. thrown by aircraft). From the coverage point view deployment can be seen as Deployment for Area-Coverage and Deployment for Location-Coverage[19]. After deployment, the network topology may change due to node failures, physical damage or battery depletion. This has led to the need to deploy new nodes to replace failed nodes[20].

Security Challenges[22]: There are increasing numbers of applications where it is considered important to protect the integrity and privacy of the data. This adds an additional burden to the processing and communication and hence power consumption of the node.

Cost effective deployment of wireless sensor networks is one of the main requirements in designing a WSN application; therefore, deploying a large number of these sensors causes the cost of a single node to dominate the overall cost of the network. Due to this, sensor nodes need to be cheap, and remain with their limited capabilities (processing speed, storage and communication bandwidth), in addition to the limited energy source making it a major challenge to design a WSN application. The network lifetime strongly depends on how these sensors can conserve their limited energy; therefore, energy management is very important to keep the network available for its intended use.

The WSN application is a collaboration of a large number of tiny sensors deployed to monitor physical phenomena, and a variety of difficulties can affect the design of the WSN. Energy consumption considered as the main design issue, which requires managing the limited energy source and achieving network longevity and other application specific quality of service requirements. In A WSN application, the total energy consumption necessary to perform the sensing task is the sum of the energy used by a single node (sense, process and send), and the total amount of energy consumed by each collaborative sensor participating in forwarding the task and sending the sensed data to the sink. Naturally, conserving energy should be considered at the node level and at the network level. To design energy efficient WSN applications, and for best management of energy consumption and gaining better energy usage, it is necessary to at first identify the energy of consumers by simply identifying what the parts are, and how much energy each part consumes [23].Secondly, energy management policies should be applied for each part by:

- reviewing the current consumption polices
- enhancing or developing new energy consumption polices

A typical wireless sensor node is comprised of four major components[1], figure 1.1

1) The sensing unit consists of a sensor (sensors) and analog to digital converter (ADC). The energy management should involve considering the factors that affect energy consumption such as by signal sampling and conditioning, signal conversion (physical to electrical), sampling rate, aliasing (the distortion of the signal that results from converting the sampled data to a digital signal) and dither (an intentionally addition random noise to the waveform to randomize quantization error).
2) The processing unit: microprocessor, DSP and storage.
3) Communication unit: the radio or transceiver
4) Power unit

Additional components could also be added such as localisation and mobilisation units, although each of these added components comes with its extra overhead energy consumption and extra energy management requirements.

To complete a single operation (sensing and forwarding) it is required to identify the participating components and how much energy is spent by each component to accomplish the task. Moreover, it is also required to identify the amount of energy consumed by the collaboration process to send the data to its final destination (sink). In other words, defining where and how the energy is used[24].

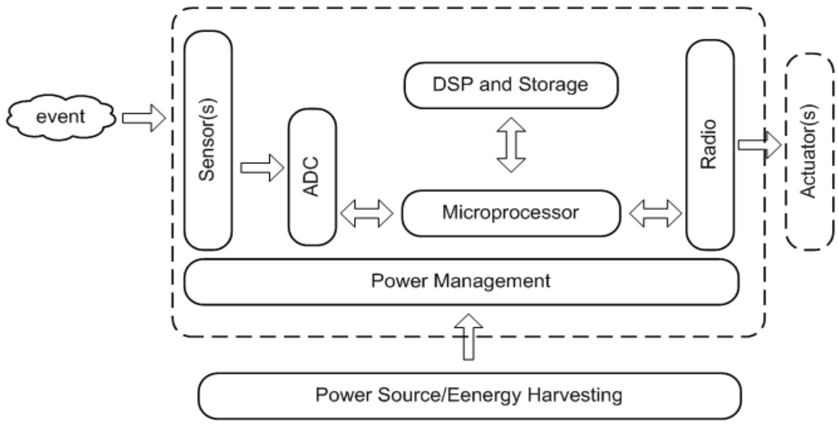

Figure 1.1 The typical components of the wireless sensor node

1.4 Research Motivations

WSNs are intended to operate for long periods, but sensors are battery operated so it becomes difficult and sometimes impossible to replace the power supply because of the high replacement cost, or sometimes due to the sensing area being inaccessible (e.g. battle field or volcanic terrain), thus wise management of the available limited energy resource is highly required to meet the design goals of WSNs.

In a WSN, a large number (tens, hundreds or possibly thousands) of sensors are densely deployed to monitor physical phenomena, and the amount of the sampled data is according to the magnitude of the network size. A potentially large number of messages are needed to forward the collected data, which makes it necessary to discover practical techniques for data management that maximise the network's life time. Reducing the number of transmitted data packets to the sink will save energy and therefore increase the life of the network[25] . Because of the rapid increase and widespread use of WSN applications in different areas, and the inability of the existing traditional protocols to meet the requirements of these applications, the development of new protocols is a vital need to keep up with the various requirements of these applications; taking into consideration the limited resources, especially energy sources, which are considered as one of the most important issues in designing a routing protocol for a WSN.

It is well acknowledged that hierarchal routing has emerged as one of the most attractive techniques that can satisfy the special characteristics of the WSN, and this has been widely adopted by the research community[26]. In hierarchical (cluster-based) routing, the network is divided into groups, with a leader for each group called a cluster head CH and normal member nodes MN. Clustering is an efficient technique for saving energy, hence member nodes send their measured data to the CH which in turn aggregates the received signals and sends it to the BS, while other nodes spend much of their operational time turning off their radio transceivers and thus saving more energy. Using data aggregation can reduce the number of data packets required to forward the collected measures; however, assigning the most energy consuming tasks to some nodes can result in the rapid depletion of their batteries. This consequently affects the network performance; therefore the rotation of the cluster heads task, among nodes through the periodic selection of a new set of cluster heads can balance energy consumption [27].

Despite cluster-based systems having the potential to save energy for static sensor networks, most cluster-based routing protocols divide the network life into a set of fixed length time rounds, thus a fixed length of time for the setup phase to partition the network into clusters, and a fixed time for the normal protocol operations to forward data to the sink. So, in dynamic clustering where imbalanced cluster sizes frequently appear, the fixed-length round time will imbalance the number of frames that should be performed during the round, and consequently cause an imbalance of the energy consumed by each cluster.

1.5 Aims and Objectives

The aim of this research is to better utilise the energy consumed by the routing process in cluster based wireless sensor networks.

The limited energy source, a sensor node, is usually battery operated. The high replacement cost in addition to the nature of the space monitored being harsh or inaccessible, makes the replacement of the power sources inconvenient in some situations or even inapplicable. Therefore, to meet the design goal potential of lifetime longevity of the WSN, this requires very wise use of the available energy.

The aim of this research is to design a set of adaptable routing protocols for wireless sensor networks that uses dynamic techniques for best usage of the limited scarce energy resource of wireless sensor networks, while considering the design goals of these networks, by:

Research Objectives

- *Study the effects of imbalanced cluster sizes on the overall energy consumed by routing operations.*
- *Design an adaptive routing protocol that uses an adjustable round time.*

- *Design a routing protocol that supports dynamic load sharing, considering the current state of the network.*
- *Design a routing protocol that can dynamically adapt various data-to-energy requirements, considering the dynamic changing of monitored phenomena.*

1.6 Contributions

The research aims primarily at best utilisation of the sensor's energy by developing adaptive techniques to increase energy efficiency. The problem of uneven energy consumption of the cluster heads during the round time will be examined.

The main contributions of this thesis are the following:

An adaptive round time controller has been developed so that the round time is calculated at the beginning of each round, instead of using a fixed time round through the system's life time. Two techniques have been proposed to calculate the round time: the first one will use the minimum cluster size and the optimal number frames as the basis for calculating the round time so that the network efficiency is improved; while in the second technique, the round time will be calculated considering the maximum cluster size and optimal number of frames so the network life time is maximised.

To overcome the diversity of the energy consumption of the cluster heads during the same round results from uneven clustering, and to reduce the effect of CH death during the operational phase, a cooperative technique has been designed so that one of the cluster members will be selected as a co-cluster head to share a part of its CH overhead. This technique has been shown to increase the number of delivered data packets.

To meet the requirements of having a general routing protocol that can support various application requirements, and can dynamically adapt various data-to-energy strategies with respect to the current use of the network, a hybrid round time controller has been designed which tolerates variable-relaxed round lengths to support various data-to- energy requirements.

1.7 Thesis Outline

The remainder of the thesis is organised as follows: Chapter 2 describes the WSN and their applications and the related work and the different routing techniques designed for WSN. In Chapter 3, the uneven energy consumption problem caused by unbalanced clustering is discussed, along with techniques that control round time. Chapter 4 proposes the co-cluster head technique for load sharing. Chapter 5 a general hybrid protocol is discussed that can adapt different application requirements. Critical review of the proposed techniques is presented in Chapter 6. Chapter 7 concludes this thesis by summarising the work and defining future research directions.

CHAPTER 2

Background

2.1 Introduction

Recently, WSNs have found their way into various potential applications. The widespread nature of such applications is motivated by the rapid developments in both sensing instruments and advances in wireless technology.

2.2 Sensor Network Applications

For security and awareness in structural health monitoring, sensors are deployed to monitor the state of structures such as building, bridges. They can detect structural changes, distortions and other structural problems to discover and identify the potentially costly or dangerous significant structural problems that can affect a structure's performance, in order to prevent the actual occurrence of a catastrophic structure failure[28].

Other potential security scenarios are found in military and battlefield surveillance applications where it is convenient to deploy a large number of these sensors over a hostile area to detect the enemy troops' movements, vehicles and tanks; also, sonic sensors can be used to detect and calculate the location of snipers[1, 2, 29, 30].

Another possible surveillance scenario of WSN is forest fire detection in order to prevent the implications of forest fires for humans and animals, through loss of forest cover, loss of habitat, water pollution, serious health hazards, as well as the destruction of invaluable wild flora and fauna in the wilderness. Sensors can be deployed over the forest floor to collect measurement data such as temperature, humidity, smoke and wind speed. Processing these data can produce a weather index, which measures the possibility of the weather causing a fire[31].

The conventional wireless ad hoc network protocol design is mainly based on a layered stack in which each layer is designed and operates in isolation. The interfaces between layers are static and independent of the individual network constraints and applications. By using this paradigm, network design can be greatly simplified. However, this approach lacks flexibility and may result in poor performance of large-scale WSNs in which resource limitation is severe, but timely delivery is required[32]. The traditional communication process in wireless networks is based on a layered stack. Each layer performs its own functions independent of any other layer, and the layers' interaction is limited to adjacent layers and through well defined interfaces, this simplifies the design and enhancement of any layer without affecting the function of other layers. Therefore, the design of each layer can be separated and completely independent of any application constraints, however the different nature of applications, their large-scale, and the limited sensor capabilities in addition to the incredibly limited energy source, make this layered model inappropriate for WSN and may result in poor performance[33]. Although a lot of effort has been made to develop energy efficient protocols for a specific layer, unfortunately they have not improved and optimised overall network performance while improving energy consumption[34]. Another trend is the integration of developing a **crosslayer** design into an entire performance management system [35, 36].

2.3 Mac Layer Protocols

Like other wireless networks nodes in WSN, these nodes share a common wireless communication medium; therefore, managing this shared medium means highly cooperation is expected to achieve the desired objectives of the network, taking into account reliable communication, throughput, latency, collision and obviously energy-efficiency[37]. Managing these conflicting factors will make it a challenge to design a scalable and energy efficient MAC protocol[38]. However, learning to manage these conflicts is essential to achieve a high-performance network, and reducing the energy waste can improve the network's overall performance[33]. Ye et al[39] have identified four major sources of energy waste in WSN: packet retransmission result from collision or congestion; the energy consumed by overhearing, overheads of control packet, in addition to the major source of inefficiency from idle listening.

To solve these problems through reducing the energy waste, Ye et al have designed SMAC, or sensor MAC[38, 40]. In SMAC, neighbouring nodes cooperate with each other to build a state schedule according to which the node can change between its wake/sleep states. The sensor node uses its wake or active period to exchange data packets or to synchronise with other nodes to adopt the schedule, while in the sleep state; nodes conserve energy by switching off their radios. SMAC uses a predefined fixed time period for wake and sleep states, so the question that arises here is what is the optimal size for each period? Because choosing a long time for the active period will increase idle listening and collision, and therefore waste more energy, but using long sleep periods will introduce more delay. in [40] the authors have proposed a dynamic solution for idle listening problems and have introduced the TMAC protocol which uses an adaptive duty cycle to control the time, so that if a sensor is expecting any traffic, it can then adjust the active time and go to sleep before its active period ends.

B-MAC[41] is an asynchronous MAC protocol. Each node maintains its active/sleep periods independently without any synchronisation with other nodes, avoiding synchronisation overheads. B-MAC reduces the communication power using long preamble, which is to some extent longer than the receiver's sleep period, so that the sender node can be assured that the receiver node will wake up during the preamble period and become active, which ensures it can detect the preamble and maintain its active period to receive that data packet. Another advantage is using low power listening (LPL) technique, so that when the node wakes up its senses the channel, and if there is no activity it returns to sleep. EA-ALPL[42] uses an adaptive technique, so that the node can set its listening state by considering the duty cycle and the working load. SEESAW [43]uses a similar idea; however, the sensors can change their modes depending on traffic patterns.

WiseMAC[44] aims to minimise the energy waste caused by the wake-up preamble for both the sender and receiver nodes. Thus, if the node knows the wake-up schedule for the neighbouring nodes, it would minimise its preamble period and save more energy. To achieve this, each node learns its neighbours' scheduled offset and uses an internal up-to-date table to maintain these offsets. Having the neighbour's schedule offset, the sender node can start sending data packets using a minimised wake-up period.

Z-MAC (Zebra MAC)[45] is a hybrid MAC protocol that improves MAC performance under high contention in networks with variable traffic patterns. Z-MAC can support both CSMA and TDMA behaviours to adapt the contention level when the traffic is low, which means low contention is expected. Z-MAC behaves as CSMA, otherwise under high traffic conditions, Z-MAC changes to TDMA behaviour. In addition, Z-MAC uses a long TDMA slot that is large enough to send two packets, so that the node can use its TDMA slot; however, if the node needs more than one slot, it can steal its neighbour's slot if it is not being used by the neighbouring node. To ensure that a slot is free, the node uses a backoff timer. If the slot is still free when the timer expires, the node can utilise this free slot to send more data. This also ensures that the owner has the priority to use the slot. **Funneling MAC[46]** is another hybrid protocol that uses both TDMA/CSMA. **Funneling MAC** uses pure CSMA in regions that are far from the sink where low traffic is expected, and for the areas that are closed to the sink it uses both TDMA/CSMA.

2.4 Routing in Wireless Sensor Networks

This section provides an overview of a variety of routing protocols designed for WSN. With a simple introduction to routing, how routing in WSN is distinguishable from MANET, a survey of different types of WSN routing protocols, and then clustering will be examined.

2.4.1 Routing Overview

Routing protocols for ad hoc networks can be classified as either *Proactive or reactive Routing Protocols*[47]:

Proactive Routing Protocols*:* proactive or table driven protocols, such as Destination-Sequenced Distance-Vector Routing protocol (DSDV) [48] or Link-state Routing. before any packet can be transmitted, routes to all destinations within the network are discovered and stored in one or more routing tables. network consistency should be maintained if any topology change occurs by passing updates through the whole network.

Reactive Routing Protocols: In contrast to proactive protocols, routes in reactive protocols are created as desired. In this type of protocol, an explicit route discovery process is initiated on a demand basis (source initiated or destination-initiated) for example AODV[49, 50].

In [50] the authors lists the following as the key differences between MANET and WSN which makes it inappropriate for WSN developers to use the routing algorithm designed for MANET:

Network size sensor networks are large scale in size (tens to thousands or more), to meet the design requirements for achieving connectivity and coverage, and to be fault tolerant, therefore more scalable solutions are needed.

Data Rate in WSN: the data rate is supposed to be very small in comparison to the data rate needed in MANET networks to transmit rich multimedia data such as video and voice.

Communication Pattern: in MANET networks each node has a global identifier, so node-centric queries can be initiated to a specific node(s) using different communication modes such as unicast, multicast, and broadcast; while in WSN, there exists no global identifier for each node, and WSN requires more collective communications, for example in data-centric applications, an attribute-value query is initiated to look for a specific measured value despite the node having the measured data.

Mobility: nodes in WSN are generally stationary or have limited mobility in a few models. However in MANET networks, nodes move in an arbitrary ad hoc manner.

Energy Management: While both MANET and WSN emphasise energy conservation, it is more critical for WSN [51, 52]because of the difficulties that could prevent energy source replacement, such as the large number of nodes, in addition to those reflected from the nature of the deployment area. Therefore, long sleeping periods for sensors and redundancy are preferred for WSN.

Application Specificity: applications in Sensor networks vary widely in their requirements. Therefore, WSN are particularly designed to meet specific application requirements, which makes it inconvenient to find one solution that meets all the needs of these various applications.

Knowledge Mining: A MANET is only concerned about networking issues. While WSN gives more prominence to data collection, processing and management[52].

Simplicity: due to sensors' limited capabilities and energy constraints, less complex and energy efficient communication and computation operations are required in comparison to those found in traditional software.

Considering the wide-range of potential of WSN applications, along with their limited capabilities, and taking into account that these diverse applications do not necessarily share the same requirements, over recent years a lot of research effort has been directed towards the development of routing protocols for WSN. This is because of the aforementioned distinctiveness of WSN and certain requirements, as well as considering the application domain and specific design goals of each application; therefore, a diverse range of routing strategies and techniques have been proposed to meet the design goals of such applications. Even so, it is no surprise that finding a general routing protocol for all WSN applications has been a thoroughly difficult and awkward task, even after several years of intensive research. Also, it is not possible to find out a "one-size-fits-all" QoS solution that fits various applications requirements [53].

Typically WSN covers a large geographical area, and it may consist of a large number of sensor nodes. Data dissemination from a specific node is routed to the sink through one or more internal nodes to form a single-hop or multi-hop communication model.

In WSN, several strategies are used for data transmission beyond the physically monitored space. Al karaka et al in [54] classify the routing in WSN into two main classes- first, *Network Structure Based* where the structure of the network is the most important issue considered in designing the routing protocol; secondly, *Protocol Operation Based* where the protocol is classified by the operations done by the routing protocol, so any of these protocols may fall under one or more network structures.

2.4.2 Flat Routing

In flat routing, the network consists of a large number of similar sensor nodes playing the same role of sensing and sending data to the sink or BS. The absence of a global identifier for each node is due to the large size of the network, so it is not usual to ask what the temperature is at sensor node 100, rather than which sensor node(s) has already sensed temperatures over 60F. As a result, data-centric routing has been used, as in spin family protocols[20], directed diffusion[21], flooding and gossiping[50].

Flooding and Gossiping: Flooding [50] is the classical approach to data dissemination, where each sensor node sends its measurements to all its neighbours; also, each of the neighbours sends the received data to all of its neighbours, until the data reaches the desired node or sink. This is the simplest data dissemination approach, but this simplicity has hazardous implications that affect the performance of the network:

Implosion: in a densely deployed area, it is convenient that each node will have several neighbours, with each node sending data to all its neighbours. Consequently, the node will receive more than one copy of the same data.

Overlap: Sensor nodes are densely deployed in a random manner, thus it is very common to find that the same issue could be covered by more than one node, so they will sense the same data.

Resource blindness: The communication activity does not consider the energy constraints of the node.

The Gossiping approach avoids the Implosion drawback by forwarding the data to a randomly selected neighbour so save energy and minimise data implosion.

Baseline Flooding the baseline assures that the sensor node can only forwards a message once, that is, no node retransmits a message that it has previously transmitted. When a node receives a message from a neighbouring node, the node will first checks whether it has already received and forwarded that message before or not. If this is its first time, the node will broadcast the message to all its neighbours. Otherwise, the message will be discarded, however flooding is energy inefficient technique because for each new message because the number of transmissions through the network is pounded by the total number of nodes, moreover the number of transmissions is also affected by collision , retransmission and packet dropping. Also the node should have a large enough cache in order to keep the received messages.

Probabilistic Flooding , in probabilistic flooding, rather than only a subset of nodes will participate in data forwarding, while the others simply discard the received messages. Once the node receives a new message it will apply a probabilistic function to generate a random number between 0 and 1, if the generated value is less than the forwarded probability $F_{probability}$ the node will forward this message to its neighbours other was it will discard the message, however one possible short come is the affect the overall network connectivity can be affected by losing some messages.

Flooding with Fake Messages the key idea of Flooding with Fake Messages is to introduce more sources that inject fake messages into the network the network this can help to prevent attacker from identifying the shortest path from the source to the sink in situations where only one source exist, thus the attacker can determine if the captured packet is faked or not as these faked messages have the same length as the real ones.

Phantom Flooding the key idea of phantom flooding is to entice the attacker away from the real source and towards a fake source, called the phantom source. Phantom flooding is a two phase routing protocol in the first phase, a message takes random or directed walk to a random node in the network (referred to as a phantom node). In the second phase, the message is flooded by the phantom node into the network to reach the base station. The message is flooded using the baseline flooding technique (referred to as flooding phase).

SPIN (Sensor Protocols for Information via Negotiation): is a family of data-centric protocols proposed to address the short comes of the classical approaches of Flooding and Gossiping[54].

SPINE-1: When new data is obtained by a sensor node, and before sending data to its neighbours as in the classical approaches, SPIN establishes a negotiation process by broadcasting an advertisement message (**ADV**) containing the description of the data (Meta-Data) obtained by the sensor. Then the neighbour(s) which has an interest in this data sends a request (**REQ**) message to that sensor node, and at the end the sensor node it sends the data to interested nodes using **DATA** message. So the SPIN solves the problem of *implosion* and the authors show through simulation that **SPINE-1** has reduced the energy consumption compared to Flooding. The node's current energy level is considered in SPINE-2 to ensure that the node can complete all the protocol operations. There are also four protocols in spin family [55] *SPIN-PP*: For point-to-point communication, *SPIN-EC* a heuristics to energy conservation has added to SPIN-PP, and in *SPIN-RL* a reliability is added to SPIN-PP for lossy channel and *SPIN-BC* designed for broadcast networks.

Directed diffusion[21] is a data centric routing protocol whose main goal is to extend the network life time by minimising energy consumption. In directed diffusion, the node generates data as *attribute-value* pairs, where the sink which requests this data creates an *Interest* which is an attribute based (*attribute-value*) *pairs* as:

```
Type = four-legged animal          // detect animal location
Interval = 1 ms                    // send event every 20 ms
Duration = 10                      // for the next 10 seconds
Confidence = .85                   // confidence in the match
Location = [-100,100,200,400]      // rectangle
```

Then the *Interest* (query) is forwarded to the entire network using multicast or broadcast. When the *Interest* (query) reaches a sensor node, the node starts to collect data about this interest and sets up a gradient to the sink or BS. If the sensor has an answer to the query it replies to the sink using the received gradient (reverse path) every second, and answer of the can be

```
Type = four-legged animal      // type of the animal seen
Instance = elephant            // instance of this type
Location = [125,220]           // node location
Intensity = .6                 // signal amplitude measure
Confidence = .85               // confidence in the match
Timestamp = 01:20:40           //local time when the event was generated
```

If the sensor has no answer to the interest, it adds itself to the gradient then forwards the query to its neighbours and the process continues until it reaches the node(s) which has the answer to the query.

Rumor Routing[56]: The algorithm assumes that the network consists of densely deployed sensor nodes. Events may occur in any part of the network, and each sensor maintains an event table that contains information about events. When a sensor observes an event, it is added to the event list with a distance of zero. Then the sensor decides whether to create an Agent or not. Where the Agent is a message with a long TTL (time-to-live), the agent has an event table containing the event and the number of hops to the event, and then the agent travels through the network. When a node receives an agent it synchronises its event table with the agent's event table. The agent dies after travelling for a number of hops. On the other hand, a node may also generate a query about an event, and the node searches its event table for a route to the event. If the route is found, the query is forwarded to that route, otherwise the query is forwarded in a randomly selected direction, and this process continues until the query reaches the node that has detected the event or the query TTL expires. The overhead for maintaining event tables and agents becomes invisible if the number of events is large[50].

2.4.3 Hierarchical (Cluster-Based) Routing Protocols

The key goal of clustering algorithms is to reduce the amount of data relayed in data packets through the network in order to reduce energy costs for transmitting data from its source to the sink. In other words, data transmission is achieved by transmitting data from source to destination through an intermediate node(s).In typical hierarchical WSN, the sensor nodes are divided into a virtual hierarchy called clusters where each node belong to only one cluster ,however some protocols accept clusters overlapping , where a node may belongs to more than one cluster[57]; a cluster is a group of nodes with a central node denoted as a Cluster head (CH). The CH is in charge of receiving members' data, carries out data aggregation, and forwards the aggregated data to the Sink. Thus, data aggregation and fusion can reduce the number of data packets required to send the sensed data to the sink. Distributing energy consumption among nodes could also prolong the network's life time.

Low-Energy Adaptive Clustering Hierarchy (LEACH)[27, 58]: LEACH is the principle routing protocol in cluster based WSN. The key idea of LEACH is that the clustering algorithm proposes to reduce the energy consumption used by data forwarding from sensor nodes to the BS, and the network life time is divided into rounds. Each round has two phases the Setup phase or Cluster formation and Steady State Phase (data transmission) figure 2.1. In the **Setup Phase**, the decision to be a cluster head is made locally at the node level. Each node *n* selects a random number between 0 and 1. If the random number is less than a threshold T(n) , the node selects itself as a CH and announces itself as a CH. Otherwise, the node will be a regular node and will wait for CH's advertisements. The threshold function is defined as:

$$T(n) = \begin{cases} \frac{P}{1-P*(r \bmod \frac{1}{P})} & : if \ \ n \in G \\ 0 & : otherwise \end{cases} \tag{1.1}$$

Where P is the desired CH percentage in the current round (r), and G is the set of nodes that has not been CH in the last $\frac{1}{P}$ rounds. Then after receiving the advertisement message and based on the signal strength of advertisement messages, a regular node elects one CH to join and send a joining message. After receiving the joining messages, the CH creates and broadcasts the transmission (TDMA) schedule. The TDMA schedule contains a time slot for each node to communicate with the CH. When a node receives the schedule table, then it can obtain a time slot and it goes sleep waiting for its allocated time to communicate with its CH.

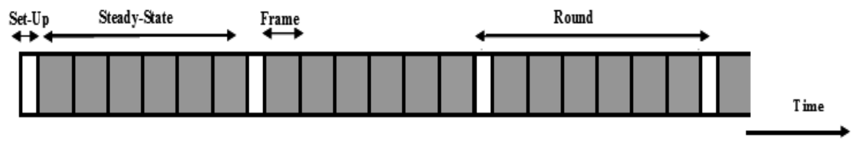

Figure 2.1: Time line showing LEACH operation. Adaptive clusters are formed during the set-up phase and data transfers occur during the steady-state phase [26]

In the **Steady State Phase** the data transmission phase is broken down into a set of frames. In each *frame* a regular node sends its obtained data to the CH (according to its TDMA time slot) then enters into the sleep mode waiting for its time slot in the next frame. Meanwhile the CH remains awake to receive all members' data. At the end of each frame, the CH aggregates the received data signals with data sensed by the CH itself and then forwards the aggregated data signal to the BS. The process will be repeated until the completion of all the frames. By the end of the last frame, the cluster has completed a single round, and all nodes enter the setup phase to select new cluster heads for the next round. Although LEACH has significant improvements compared to traditional protocols, much attention has been dedicated toward solving some of the problems of LEACH, such as the head selection scheme and the single-hop transmission. Therefore, different metrics have been considered in implementing the probabilistic function, such as the current node residual energy cluster sizes, cluster diameter, and the distance from the BS, in addition to various multi-hop methods which have been proposed.

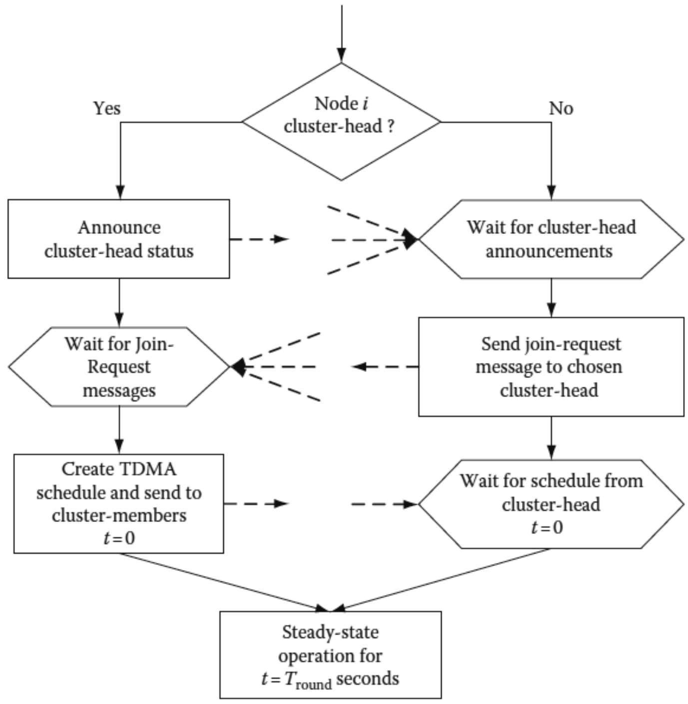

Figure 2.2 flow-graph of the setup phase of LEACH

In [59] a time based scheme has been introduced to divide the network into four clusters. Each node adopts a random timer, and if no CH advertisement is heard, or if the number of a advertisements is less than four, the node announces itself as a cluster head and waits for joining messages. In[60], a general threshold sends the node energy level and the desired number of clusters, in addition to the threshold function used in leach selecting the CH. Zhixiang et al in[61] have proposed a two hop transmission scheme to reduce this. In[62] the network is divided into different layers, and the communication is achieved by sending data through the CHs in each layer. In [63] the relative distance from the BS in addition to the node's current energy level are considered in the head selection function. For EEUC [64] the network is partitioned into unequal cluster sizes to avoid the hot spot problem, and in multi-hop routing, CHs closer to the BS are dedicated to forward other cluster's, so a similar principle is used. In [65]a new energy efficient clustering algorithm for Wireless Sensor Networks EECS nodes residual and its level are considered in head selection, and the data dissemination is achieved though multi-hop.

In LEACH-D[66], the cluster diameter is used as a metric in addition to multi-hop routing. In [67] the distance from the BS and the nodes' energy lever are used in selecting the CH in addition to 2-Hop. In [68] a two layer multihop routing schemes is proposed, where the sensing coverage is considered in cluster head selection. In [69] the cluster head selection considers the nodes' density over a specific area and data transmission is achieved by multi-hop, and the cluster head rotation within the same cluster considers the node's energy level.

LEACH-C[27] is a centralised cluster based protocol. The cluster formation process is performed by a centralised algorithm executed at the BS. The BS itself selects some nodes to be cluster heads considering the residual energy at each node. In the Setup phase of LEACH-C, all nodes send their location and the current level of energy to the BS. Based on the node's current energy level, the BS elects a set that can act as cluster heads for the next round. Then the BS applies the simulated annealing algorithm to partition the network into a predefined number of cluster k, which is 5% of the total number of nodes[58].

Once the clusters have been identified, the BS broadcasts the clustering information message that contains the cluster head *Id* for each node. When the node receives the message, if the cluster head *Id* in the message matches its *Id*, the node takes on the task of the Cluster Head, changing its status to wake up and waits for members' data; otherwise it determines its time slot and enters into sleep mode. A steady state in LEACH-C is as in LEACH, and another centralised approach is combined. In [70] the clusters are formed once and temporary-CH and CH are defined for each cluster, the temporary-CH is responsible for selecting the cluster head for the next round, based on the nodes energy level, however the problem of static clustering is that , it is not possible to add new nodes to the network to replace failure nodes, secondly the robustness are determined by the ability of the temporary-CH to exist, hence if the temporary-CH dies for any reason such battery depletion or physical damage all the cluster’s members will lose the communication with the BS.

In [71] a centralized fixed ring scheme is proposed , at the beginning the BS divides the network into a set of clusters , where nodes use a ring-based for intra-cluster data disseminations , the cluster sender role is periodically rotated, however in fixed networks it is not possible to add new nodes ,moreover if the CH died all cluster members will lose communication with the BS , also ring based communications is affected by all members existence, in other words if any nodes failed all data forwarded through this node will be lost. In [72] the authors propose BCDCP a centralized clustering protocol, which aim it to balance the number of members in each cluster and Use CH-to-CH so that one of the cluster heads is randomly chosen to forward the aggregated data to the sink, a similar approach is used in self organizing networks[73].

HEED [74] is a self organising clustering routing protocol, its main goal is to prolong the network life time. HEED selects a set of nodes as cluster heads depending on the residual energy of the node as the primary parameter and intra-cluster communication cost as a secondary parameter for cluster head selection .In the clustering process in the initialization phase: each determines if it tentative cluster head or not ,this depends on its current residual energy, secondly node enters the repetition phase where each node try to elect one of the tentative cluster heads, the head selection is based on intra-cluster communication cost , after the cluster heads selection, non cluster heads nodes (normal members) decide to join the cluster head with less communication cost ,then operational phase starts.

In[75] the authors proposed an enhancement to HEED in order to reduce the number of CHs , the clustering algorithm is re-executed for those not that are not hear from any cluster head. In [76] each node computes a weighted a function of the residual energy and the number of neighbors, the node with the heights weight is elected as a cluster head.

TEEN Threshold sensitive Energy Efficient Sensor Network Protocol[77]:

TEEN is a cluster based routing protocol based on LEACH. The main goal of TEEN is to reduce the energy consumption using Hard Threshold (HT) and Soft Threshold (ST) to control the number of forwarded readings. When a sensor node has a new reading, then the (SV) is forwarded to the CH if it is greater than the (HT) or at least differs from the previous sensed value (SV) by the (ST). The network performance is highly dependent on the threshold values- a small (ST) will give a more accurate view of the network; however there is more data transmission, and consequently more energy consumption. Because the sensor may spend long periods sensing but not forwarding using big (ST) or (HT), this makes TEEN not suitable for applications where periodic reports are needed. **APTEEN** (Adaptive Periodic Threshold-sensitive Energy Efficient Sensor Network Protocol)[78] is a hybrid routing system that uses two communication policies- proactive as in TEEN and reactive as in LEACH. To avoid the problem of the potential long period of time that the node may spend sensing but not sending, the node is forced to forward its data if it is exceeds the value of Count Time (TC), which controls the duration between any two successive reports. Moreover, APTEEN supports different types of queries: historical, one-time and persistent queries to respond to the user’s requests. However, the main shortcomings of both TEEN and APTEEN are the complexity of implementation of the threshold values and overhead, and the complexity of forming multi-level clustering[50].

PEGASIS [79]is a chain-based protocol that forms where a node only needs to communicate with is closest neighbours. To build the chain, PEGASIS uses a greedy algorithm, starting from the farthest node from the BS, and tries to find a neighbour that is closer to the BS. Then, each node sends its observations to its closest neighbour until all the data is aggregated at the chain leader. After that, the chain leader sends the aggregated data to the BS on behalf of other chain members. PEGASIS reduces the overall energy consumption by minimising the transmission distance, because each node sends data only to its closest neighbour. However, PEGASIS assumes that each node has global knowledge of all node locations, but it is not referenced by which methods nodes could obtain these locations. Moreover, there is excessive delay for distant nodes on the chain[54].The significant overhead for topology adjustment requires awareness of the node's neighbours' status, especially for highly utilised networks[80].In [81] the authors proposed to chain-based routing scheme , the first one with CDMA, and second one used a three-level chain-based routing without CDMA nodes.

2.4.4 Location Based Routing

Location based routing uses the sensor's location as a base to set up an energy efficient route from the source node to the sink or BS, so that the query about this intended data can be disseminated to the specified area, avoiding the extra energy overhead from sending the query out to the specified region [80].

Geographic Adaptive Fidelity GAF [82]divides the physical space of the network (sensing field) into virtual squared cells (grids). Then the sensor nodes enter a discovery state to discover all their neighbours which share the same cell space. After the discovery state Td, after the Td the node enters the active state(Ta), so that it is responsible for performing the sensing and forwarding tasks, while the other nodes enter into sleep state for a time(Ts), saving their energy. After a period of time (Ta), the node starts a discovery state up again to give other nodes the chance to be active.

Geographical and Energy Aware Routing (GEAR])[83]: the main idea of GEAR is to minimise the amount of interest in directed diffusion, rather than flooding the interests to the whole network. GEAR uses a heuristic technique to select one neighbour with the lowest cost to forward the packet to the target region. Moreover, for packet forwarding within a region, a recursive geographic forwarding technique is used.

2.4.5 Quality of Service Routing (QoS)

The general characteristics of WSN and the application specificity, in addition to the traditional QoS metrics (inherited from ad hoc networks) means new QoS requirements should be considered in designing WSN applications.

The Sequential Assignment Routing (**SAR**)[84] maintains multipath routes from the sensor nodes to the sink. For route construction, SAR constructs tree rooted at the source, where for nodes the energy and QoS factors are considered while adding the node to the path. When a packet is generated, the node must decide which path the packet should follow to reach the sink, while considering the packet's priority, the amount of energy needed along the path, and delay. For example, a packet with high priority need to be forwarded through a minimum delay path which may consume more energy, so the node should decide which path to select for packet forwarding. Some paths may change as a result of the failure of some nodes to enforce consistency, so a recovery procedure using handshakes between upstream and downstream nodes is performed.

A Stateless Protocol for Real-Time Communication In Sensor Networks (SPEED) [85, 86]:

SPEED is a stateless routing protocol for soft real-time communication; each node maintains information about its neighbour, and path finding is achieved by using a geographic forwarding technique. The end-to-end delay depends on the distance from the source to the destination. This delay can be calculated by the application for the available packet before taking the route decision to calculate the end-to-end delay. The distance between the node and the sink is divided by the estimated

SPEED. In addition to QoS support, congestion management and load balancing is also provided by SPEED, however SPEED does not consider any further energy metric. MMSPEED (Multi-path and Multi-SPEED) [86] is concerned with guaranteed packet delivery rather than energy consumption. A localised decision for packet forwarding is made, using only local-node neighbour information, so no prior route setup or route state are needed. MMSPEED provides different QoS options for timeliness and reliability domains. For the timeliness domain, there are multiple network-wide speed options, so the intermediate node can choose between increasing the packet speed to fulfill its delay deadline or achieving the reliability requirement using probabilistic multipath forwarding.

In addition to the coverage problem considered as a metric for QoS[87], and the coverage problem has been addressed in various routing schemes , holes detection[88],another important issue related to coverage problem is to define the minimum set of nodes that cover a specific sensing region while other redundant nodes can be switched off to save energy[89], network connectivity and coverage constraints[63]. In[90] the coverage of sensing area is considered as a selection parameter in selecting the cluster head . In CPCP[91], the head selection consider the coverage-aware cost metric , and for wireless sensor and actuator network the location of the actuator from the cluster head is considered to maximise coverage[92].

2.5 Problem Definition

In this section, the problem of using fixed round time will be examined including how this affects energy consumption. In designing a cluster-based WSN it is important to consider the special attributes of the cluster-based WSN attributes, such as the number of clusters; how frequently clusters are rebuilt; cluster size, and number of hops (single hop or multihop), in addition to the most crucial aspect which is energy consumption. Such a perception and awareness forms the basis for a general discussion about clustering problems and potential solutions that can assist in designing the network, and how the available energy can be spent in a proper way that conveys with the intended design goals of the WSN application. Energy utilisation to improve the network performance is, then, a great challenge in designing WSN.

The problem which is being addressed here is that communication is the most expensive, and in general, the larger the number of bits transmitted, the greater the energy consumed. Furthermore, nodes in WSN are equipped with small limited energy batteries. This limitation arises from the physical size and the cost of these sensors meeting the inexpensive deployment costs of such applications. Accordingly, the aim is to ensure as efficient use as possible of a given energy. For data dissemination, this means that it is intended to obtain as much data as possible for a particular given energy. The network lifetime is the main constraint on achieving this efficiency. For network longevity, the efficient use of the available energy will prolong the life time; however, achieving this is constrained by the amount of data to be sent.

2.5.1 Cluster Size Variation

Part of the simplicity of the LEACH-C protocol is that it selects a set of candidate nodes based on their current energy level, and then assigns cluster heads by applying the simulated annealing algorithm entirely to the sensors across the sensor field. With this approach, clusters are constructed subject to the optimisation function which minimises the total energy cost of the intra-cluster communication for each round.

When applying this clustering scheme, clusters can be created of various sizes, and clusters can vary considerably during the system's life time. This can be noted from Figure 2.3 which plots the minimum and maximum size of clusters.

A frame of large clusters takes more time to complete than the time required for smaller ones. Therefore, small clusters will carry out more frames during the same period of time. This means that members will send more data signals and the cluster and head needs to communicate more frequent with the BS in order to send the aggregated data signals that results a variance in the energy consumed by each cluster head.

To study the performance of LEACH-C, several simulations have been created, using the system parameters of [27]. For example, to illustrate the effect of this, figure 2.4 shows the nodes distribution at round (Ri), in figure 2.5 we plot the number of messages received by each cluster head and the energy consumed by cluster head to aggregate and send the received data signals during the round Ri, it is observed that CH1 sent less data messages than CH2, although CH1 spent more energy during the same round than the CH2. Moreover, CH1 is closer to the BS than CH2. The reason for this is the CH1 performs more frames during the same rounds. Actually, from Figures 2.4, 2.5 it is clear to show how the variable load has a significant effect on unbalancing the energy consumption between heads, and this consequently affects the overall network performance.

Thus, in dynamic clustering, small size clusters might be located at any location in the sensing area, so the load of individual heads can vary. Therefore, cluster heads with different loads will perform a different number of frames, which can unbalance the energy consumption and increase the diversity in energy consumption between different cluster heads. This diversity can increase as the length of the operational phase increases.

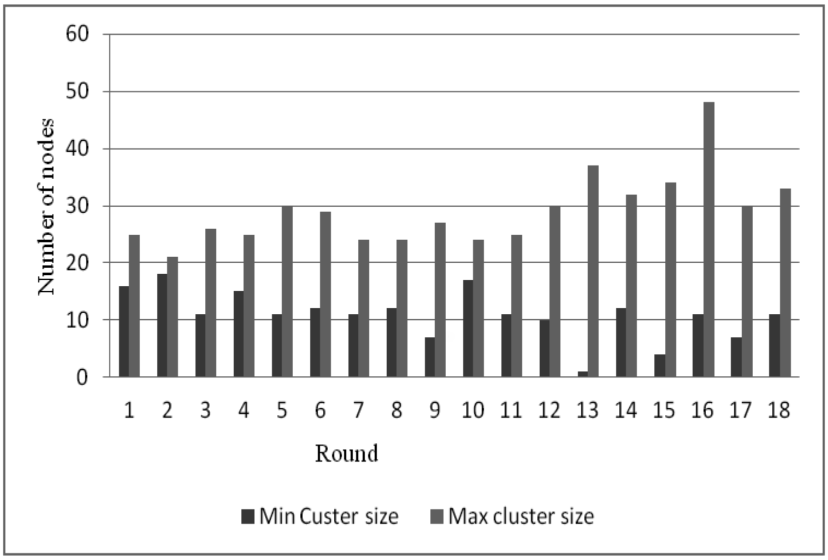

Figure 2.3 the maximum and minimum cluster size in each round.

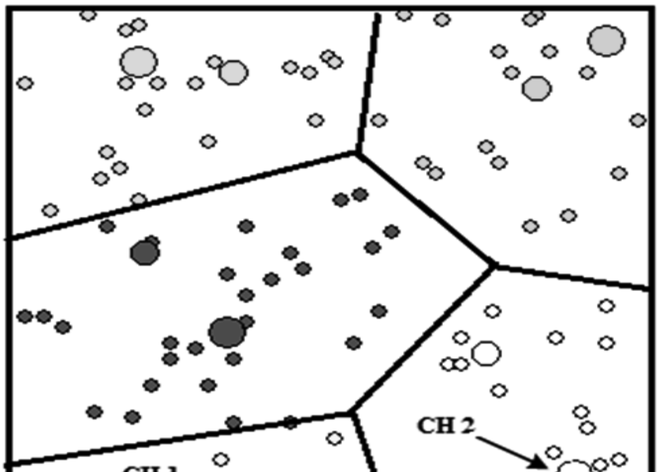

Figure2.4 the nodes' distribution at around Ri

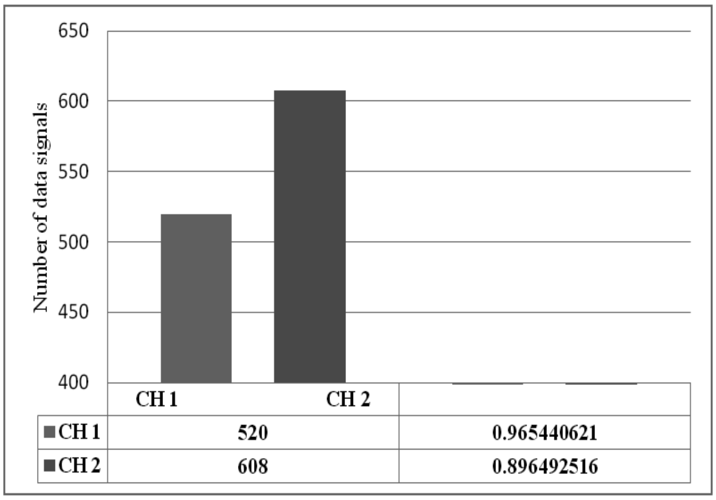

Figure 2.5 the number of data message represented by the messages send by CH1 and CH2 ,with energy spent by each cluster head to receive, aggregate and send these messages .

2.5.2 The Death of the Cluster Head

Another observation while studying the performance of LEACH-C is that CH head death during the round is very common, especially when the residual energy of nodes declines as the network progresses. In this case, node operations are determined by the TDMA schedule, therefore nodes' active periods will be scheduled accordingly. There is no way in which nodes can maintain the CH status, thus if the CH dies during the round's operational phase, the nodes will continue sending their sensed data signals in spite of the CH status. Consequently, the energy waste will increase because the energy consumed to send these messages is considered to be wasted energy; hence if the CH is dead it won't be able to receive these signals. For example, assuming that during a round r_i which starts at time t_0, a CH dies at time t1 which is smaller than t2, this denotes the time when the round ends and Δt is $(t_2\text{-}t_1)$. Thus the energy consumed by the member's transmissions between t_1 and t_2 will be considered a waste of energy because members are sending data while the CH is dead. As a consequence, as Δt increases, the resulting energy waste will increase accordingly.

Despite many clustering techniques having been proposed to improve network performance, few investigations have considered round time. In [93] the round time is computed considering the current residual energy for both the CH and non cluster, in addition to the number of live nodes, without details on how distribute the number of nodes alive. However, in distributed clustering algorithms it is not possible to determine the number of live nodes without an extra communication overhead. In VR-LEACH [94] a constant value of the frame length is used to determine the round length, where these values are experimentally defined. In addition, in both schemes, it is not stated how the new round length can be distributed to the whole network. In view of the problems discussed so far, chapter 3 and chapter 4 of this dissertation focus on the potential solutions.

CHAPTER 3

The Variable Round Time Techniques

3.1 Introduction

Optimising energy utilisation to improve network performance is a great challenge in designing WSN. Yet measuring the network performance is sometimes confusing. For the large part, extending the network lifetime is seen as a significant improvement that meets the longevity design goal, while the amount of disseminated data is no less important, because in some situations if the network fails to forward important readings, it can undermine the network's application or can be disastrous.

As discussed in section 2.5 using fixed-time rounds can affect network performance where uneven clustering commonly occurs. The objective is to demonstrate that variable round lengths have can be a key role in cluster based routing to achieve energy-efficiency and network performance.

Two main areas where round time can have an impact on energy efficiency routing are extending the network lifetime, and increasing the number of forwarded messages. The first is more general; however it is supported by the second. The techniques described in this chapter are built on previous work with LEACH-C by focusing on the significantly varying network performance when applying round controllers.

The effect is evaluated here from two dynamic round time controllers which have been analysed. The first technique, VAR-RC, is described in section 3.2 and is a round controller that aims to reduce the overload of the CH which has fewer members to maximise the network lifetime. Therefore fixed and extended slots are considered. The second technique, MIN-RC, is presented in section 3.3. This technique can improve the overall network throughput by minimising the round time, thus the excessive energy consumed by the head of small clusters can be decreased.

3.2 Variable Round Time Controller (VAR-RC)

Most of the routing protocols based upon the principals of LEACH divide the network life span into a set of fixed-time rounds. In dynamic system it has been shown that using fixed-round time results in unfair distribution of load. As mentioned in section 2.5, the smaller clusters would spend more energy sending less data during the same round, and this can have a great impact on the overall network performance. To solve the problem of excessive energy consumption and to minimise the imbalance of energy consumption we propose a new protocol using a Variable Round Time Controller (VAR-RC). VAR-RC uses an adaptive method to reduce the diversity of energy consumption among nodes. The focus here relies on changing the round time dynamically, aiming to improve the network's lifetime, while considering the amount of data received by the BS.

As explained in the previous sections, under LEACH-C, smaller clusters introduce more frames during the same round, and consequently there is extra energy inefficiency. VAR-RC aims to minimise the extra energy consumption that results from the unbalanced workload and reduces the intra-cluster communications. The key idea of VAR-RC is to extend the round time, so that large clusters can perform the optimal number of frames, while smaller ones are protected from sending more frames, thus reserving more energy. To do this, VAR-RC uses a scaled frame for the small- sized clusters. The frame time is specified by the number of members per cluster and the slot time assigned to each member to communicate with the CH. The overall idea of frame time scaling is achieved by adjusting the slot time, thereby minimising the extra inter and intra cluster communications overhead. Another advantage or benefit from stretching or extending the slot time of some clusters is that nodes in different clusters would have the same opportunity to turn off their radio and enter into sleep mode during the same round.

3.2.1 The Modified Round Time

The round time is extended to allow the cluster with the largest number of members to complete the optimal number of frames. On the other hand, the slot time for smaller clusters is adjusted to prevent the sending of extra frames, meaning that all clusters will perform the same number of frames that is equal to the optimal. To gain an understanding of frame time scaling, figure 3.1 illustrates the scaling example. Consider that there are two clusters *C1, C2* with sizes, m and n respectively, where m is less than n, if it is assumed that the frame time for the cluster *C1* is F_{t1}, then the frame time for *C2* would be larger than F_{t1}. This is because a fixed time slot is used by all clusters figure 3.1. To provide fairness among clusters and prevent extra overhead messages, the smallest frame, which is frame1, should be relaxed by increasing the value of the slot time σ as in figure 3.2, to ensure that both clusters will perform an equal number of frames. The network thus minimises the energy inefficiency caused by cluster based sensor networks of multiple cluster sizes that are frequently found in such dynamic systems.

The network lifetime of VAR-RC is broken down into controlled variable-time rounds, where the length of each round ($T_{current}$) *is* defined at the beginning of the round $R_{current}$ and depends on the optimal round time (T), the maximum cluster size (C_{max}) and the optimal cluster size (N/K).

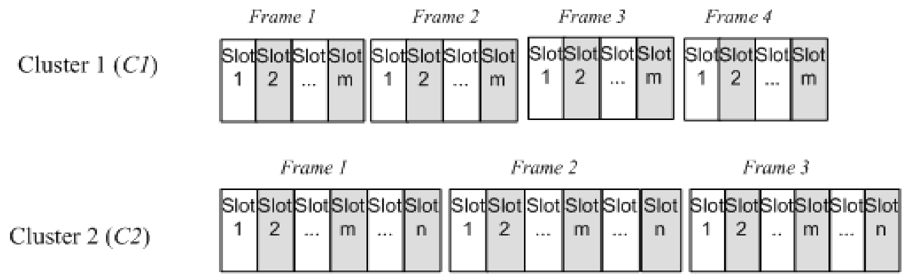

Figure 3.1 the original frame-time of cluster C1 with m members and the frame time of the cluster C2 with n members , where n>m, C1 will accomplish more frames than C2 during the same round.

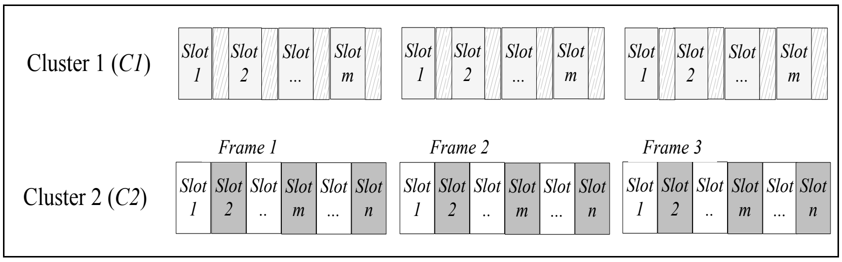

Figure 3.2 the modified frame-time for a cluster C1, each node starts its wakeup after the pervious node in the schedule finishes its time slot plus the relaxed value, determined according to the n which the maximum cluster size, both C1 and C2 will send the same number frames during the same time.

The round time in VAR-RC has two phases, the setup phase and the operational phase figure3.3. The setup phase starts at the beginning of each round, nodes start sending their information (Id, location and the current energy level) to the BS, then the BS performs the simulated annealing algorithm to partition the network into k clusters as in LEACH-C and creates the TDMA schedule for each cluster; in addition, the BS calculates the operational time for the current round ($T_{current}$), and after determining the value of $T_{current}$, the BS sends both the TDMA schedule and the modified operational time ($T_{current}$).

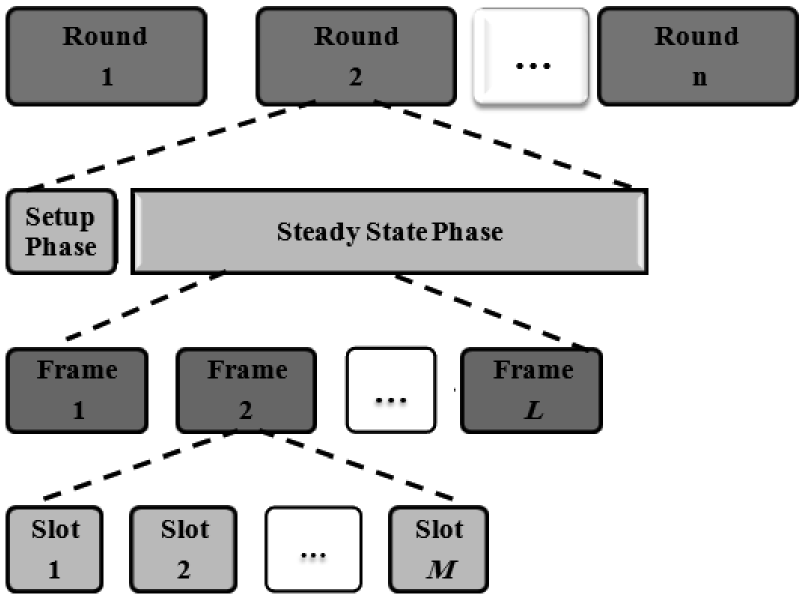

Figure 3.3 the network life time, the network partitioned into clusters in the Setup phase, members to CH data transfer and CH to BS data sending are done during the Steady-State phase.

Now the calculation of the operational phase's length will be discussed in detail, assuming that:

N: is the network size (number of sensor nodes)

K: is the number of clusters

R_i: stands for the current round

C_{ij} is the cluster j at the round i, where j: 1… K

CH_{ij} the cluster head of the cluster C_{ij}

M_{ij} the size of the cluster C_{ij}

T the optimal round time as discussed in [95]

Heinzelman [95] defined the optimal cluster size, the average number of frames per round and the round length and definition is used by most research in field. It has been assumed that the network consists of N nodes that are uniformly distributed in A xA region, if there are k cluster then the average number of nodes per cluster is is $\frac{N}{k}$, so the area occupied by each cluster is $\frac{A^2}{k}$, and it assumed that the area is a circle with radius R, where the node distribution is $\beta(x, y)$,so the energy consumed per cluster $E_{cluster}$ is

$$E_{cluster} = E_{CH} + \frac{N}{k} E_{non-CH} \tag{3.1}$$

Where E_{CH} is the energy dispatched by the head to receive N/k messages , aggregate the received message and forward it to the BS, and $E_{non\text{-}CH}$ is the energy consumed by the a normal node to send its reading to its cluster head, so the total energy consumed is

$$E_{total} = k\, E_{cluster} \tag{3.2}$$

Then E_{total} was derived with respect to k to 0.

In order to define the length of the round and how often the clusters should be rebuilt, the energy consumed by the CH during the round $E_{CH/round}$ is

$$E_{CH/round} = N_{f/round} * E_{CH/frame} \tag{3.3}$$

And the energy consumed by a $E_{non-CH/round}$ is

$$E_{non-CH/round} = N_{f/round} * E_{non-CH/frame} \tag{3.4}$$

Where$N_{f/round}$ is the number of frame per round and $E_{CH/frame}$ the energy dispatched to complete a single frame, under the assumption that nodes are evenly distributed with $\frac{N}{k}$ nodes per cluster, the rotation method ensures that each node's energy last enough to allow the node being a cluster head once during $\frac{N}{k}$ rounds and non cluster head $(\frac{N}{k} - 1)$ the they compute the round length assuming that a simple radio model is used, further details of these calculation can be found [95].

Thus once the round time T has been defined in addition to the desired number of clusters k, then number of average frames can be computed. However, as mentioned earlier, in dynamic clustering, clusters' sizes might vary, so the load of individual heads and members can vary accordingly, this raises the need to have a dynamic techniques to adapt such situations.

Without loss of generality, at any round Ri there will be k clusters of size Mij resulting from the partitioning process.

For any cluster C_{ij} with M_{ij} members, the length of the TDMA schedule, which is the time required for all members in the cluster to send their data to the cluster head CH_{ij} is defined as $\sum_{m=1}^{M_{ij}} \sigma$. σ is used to denote the time slot assigned to each node to communicate with its CH, and total time required for a cluster to complete a single frame is:

$$F_{ij} = \sum_{m=1}^{M_{ij}} \sigma + \lambda \tag{3.5}$$

Where λ stands for the time required by the cluster head to aggregate the received data and send the aggregated packet to the BS. In even clustering the optimal cluster size is *N/K* the optimal TDMA length $\sum_{m=1}^{N/K} \sigma$ and the optimal number of frames is:

$$N_{f\_average} = \frac{T}{\sum_{m=1}^{N/K} \sigma + \lambda} \tag{3.6}$$

For a cluster C_{max} which has the maximum size (maximum number of nodes M_{max}), the frame time (F_{max}) is always greater than F_{averge} , thus C_{ij} will complete less frames than the $F_{average}$. On the other hand, smaller clusters will complete more frames. To ensure that any cluster can perform the $F_{average}$ frames, the $T_{current}$ is extended and defined as follows:

$$T_{current} = N_{f_{average}} * F_{max} \tag{3.7}$$

The setup phase of VAR_RC ends by partitioning the network into *k* clusters, identifying the head of each cluster and the length of the operational phase, and after that the BS broadcasts the clustering information as well as the length of the current round for the operational phase.

Whenever a node receives the clustering information, it can determine its role (either a CH or normal member node). If the node is a normal member then it can determine its cluster head and its time slot in the TDMA schedule, however to insure that the node will not perform more frames than the average number of frames $N_{f\_average,}$ it modifies its time slot σ as follows:

$$\sigma_{ij} = F_{max} - \lambda / M_{ij} \tag{3.8}$$

And the adjusted frame length for each cluster will be:

$$F_{ij} = \sum_{m=1}^{M_{ij}} \sigma_{ij} + \lambda \tag{3.9}$$

The member node can now schedule its active and sleep modes using the modified slots, and use the modified slot to send its data to the Cluster head.

So that the frame length should be equal to F_{max} it implies that no cluster can send more than $N_{f\_average}$ frames, thus balancing the number of frames performed by each cluster and avoiding excessive energy consumption.

If the node is a cluster head it can determine its members, the frame length, as well the length of the operational phase in the same way. Then the node changes its role to a CH and remains awake during the operation in order to receive members' data according to the modified TDMA schedule. When the CH receives the reading from the last node in the schedule it aggregates the received data with its own and sends it directly to the BS, that is, the cluster completes the current frame and is ready to start the next one, according to the modified TDMA schedule.

3.2.2 Simulation of VAR-RC

Having described the round time controller VAR-RC, the NS2 simulator[96] was used in addition to the LEACH-extension[97] to simulate both techniques in order to demonstrate the effects of the round time controllers on network performance. During the simulation, the node's energy level was tracked after any packet transmission or receiving; the node's death time; the data loss caused by the head's death; the amount of data sent by each node, as well as the amount of data messages received by the BS. We now turn to illustrating the performance metric used to evaluate the proposed techniques, and the efficiency of the proposed methods, measured in terms of the network lifetime, and the number of data messages received by the BS and the amount of energy consumed for each delivered data message.

The network lifetime is the lifespan from the deployment to the time that the network is considered as nonfunctional. However, when to consider that the network is nonfunctional is an application specific, and different measures are used to evaluate the network's functionality, such as when the first node dies (FND), the time when the half node dies (HND), last node dies (LND), or when a percentage of nodes are dead. Moreover, the network connectivity or the loss of coverage can be used to identify the network's functionality[98]. The number of nodes alive over the time was used to measure the network lifetime. If the nodes alive during the simulation time can be tracked, a node is considered to be alive if its residual energy is over a minimum threshold, otherwise the node is considered to be a dead node. Dead nodes are unable to send or receive any data, and it is considered that the network is nonfunctional when the number of nodes alive is less than or equal to the desired number of clusters, so that network lifetime is the lifespan from the nodes' deployment to 95% of nodes dying.

The number of delivered data messages is another measurement used to evaluate the network performance of the proposed methods, where the data signals are sensed by the cluster's members and sent to the cluster, and are then aggregated with the head's own measure into a single signal and sent to the BS. Thus as the number of the aggregated signals is increased, the most clear image of the monitored phenomena would be achieved; therefore the number of aggregated signals for each data packet received by BS has been tracked. Then the average energy cost spent per delivered data message has been computed to measure how these methods can best utilise their energy.

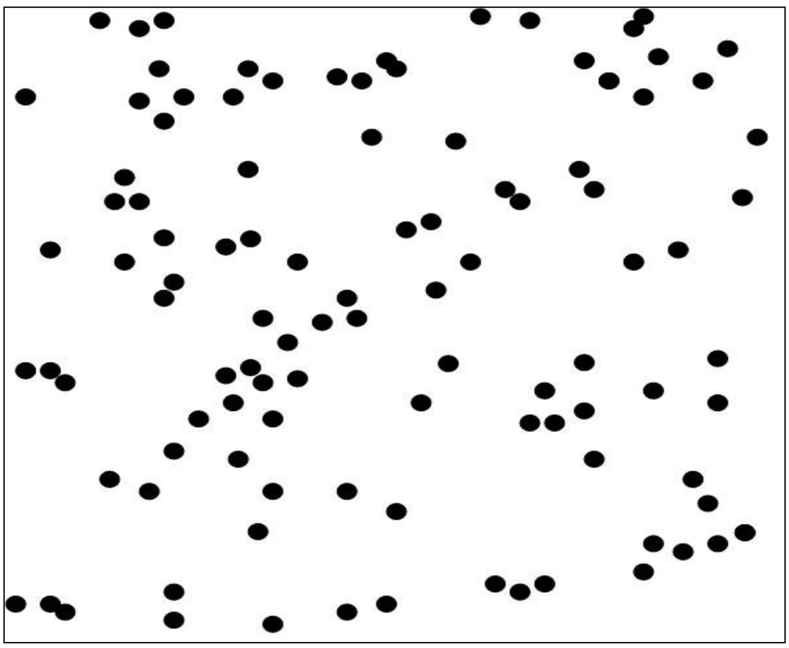

Figure 3.4 the distribution of the sensor nodes over the sensing area, the BS is not shown in the figure.

In the experiment a network with 100 nodes that are randomly deployed over the sensing area between (0, 0) and (100,100) has been considered, as shown in figure 3.4, and if sensors always have data to send. The BS is located far away from the sensing area. Figure 3.4 shows the topology used in the simulations and it has been assumed that all nodes are homogenous and start with the same energy level. All nodes are immobile, and each sensor node can change its radio transmission power to send directly to the sink. Table 3.1 summarises the values of the system parameters for the simulation model, which are similar to those used in LEACH-C. The simulation ends when the number of nodes alive is less than or equal to the desired number of clusters. In this experiment we conduct 5 trials for each protocol and the average the total delivered for all trails has been computed, and the trial that minimises the variance of the average is selected, although the maximum variance from the average was less than 1%. The simulation results show that nodes under VAR-RC have a longer lifetime compared to those using LEACH-C for different lifetime metrics.

Table 3.1 the system parameters used in the experiment

Parameter	**Value**
Sensing area	100 x 100
Network size	100 nodes
Location of BS	50,175
Data message	500 bytes
Packet header	packet type 25 bytes
Initial Energy	2J
E_{elec}	50 nJ/bit
ϵ_{fs}	10pJ/bit/m^2
ϵ_{mp}	0.0013pJ/bit/m^4
Number of cluster s	k=5.

Figure 3.5 illustrates the number of nodes alive during the simulation time. The results show how the VAR-RC extends the network lifetime compared to LEACH-C, and the percentage of the lifetime improvements of VAR-RC is further illustrated in table 3.2, using different lifetime metrics, the time when the first node died (FND),

the time when half of nodes died (HND) and the time when the last node died (LND). The results show how VAR-RC performs better than LEACH-C in terms of the lifetime. In LEACH-C all nodes remain alive for 350 seconds before the first node dies, while in VARRC all nodes remain alive for 418 seconds, which means that the improvement of the network life is 19.4% using the first node died FND evaluation scheme. Concerning the improvement using the half of nodes die HND scheme, the improvement to the network life time is 15.1%. Furthermore, comparing this protocol to LEACH-C using the last node die LND (95% of nodes die) evaluation scheme shows that the network life time in this protocol is longer than LEACH-C by 19.9%. Moreover, figure 3.7 illustrates different percentages of dead nodes during simulation time. This figure shows that VAR-RC is better than LEACH-C during the network life time and proves that nodes LEACH-C die earlier than VAR-RC.

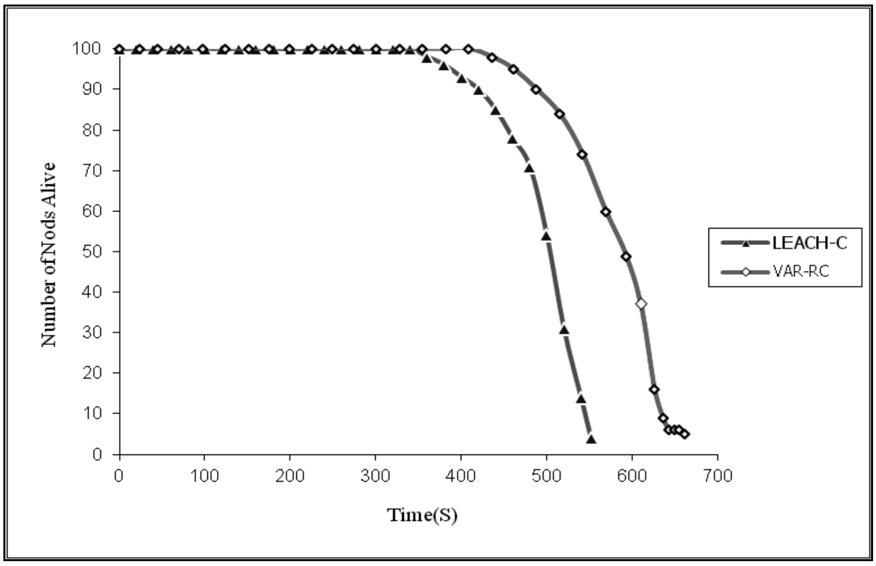

Figure 3.5 The number of nodes alive over the simulation time, compares VAR-RC with LEACH-C .

Table 3.2: the percentage of improvements of VAR-RC compared to LEACH-C using different lifetime evaluation metrics

	VAR-RC	LEACH-C	Improvement
F ND	418	350	19.4%
HND	578	502	15.1%
LND	661	551	19.9%

After illustrating the effects of using VAR-RC on the network lifetime, the effect of the VAR-RC on the number of the delivered data messages will now be revealed. Figure 3.6 shows the number of delivered data messages by each node from the time the simulation starts until the first node dies. From this figure it can be seen how the VAR-RC maintains the amount of delivered data messages and all nodes send nearly the same amount of data during this period.

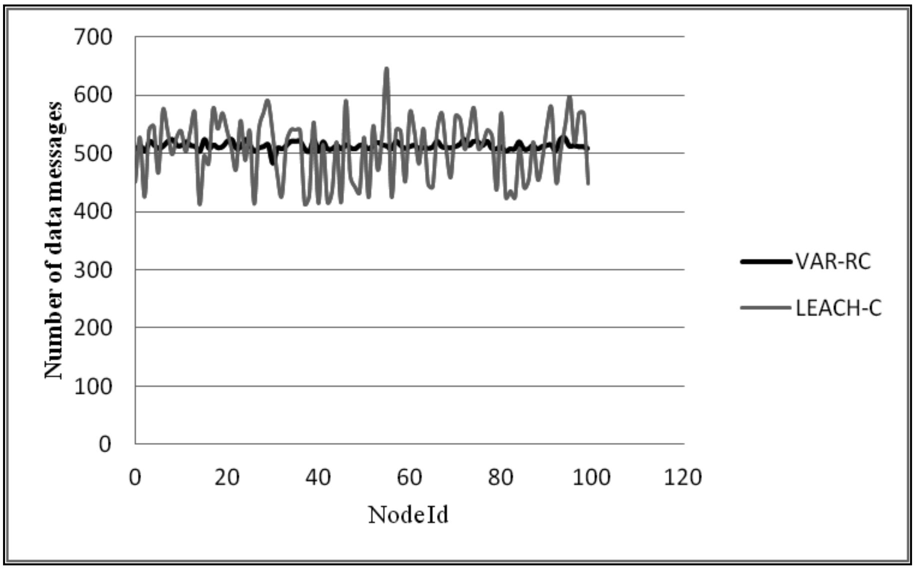

Figure 3.6 the number of data messages received from each node, at the end of round 17, before the first node die under LEACH-C.

Figure3.8 illustrates the number of received data messages by the BS; it shows that VAR-RC delivered less data messages compared to LEACH-C.

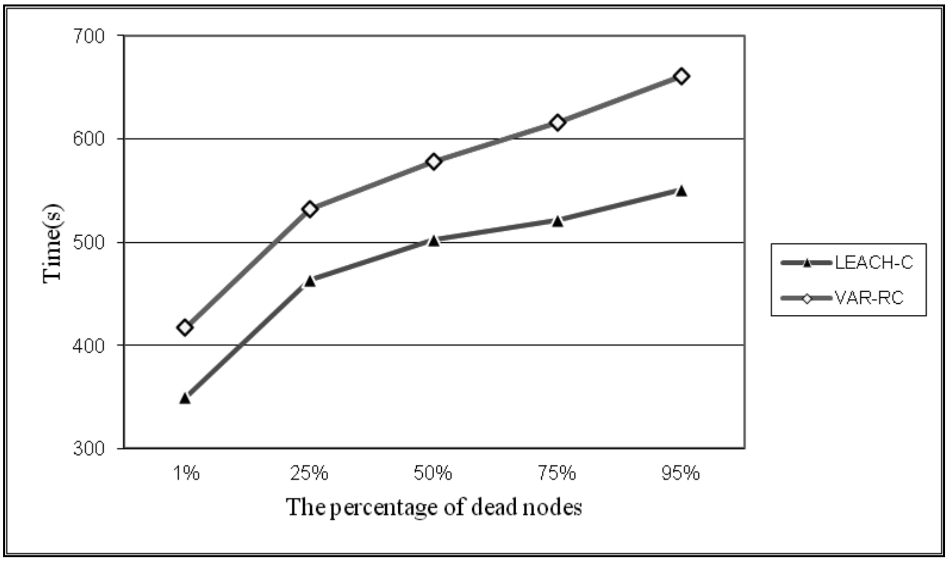

Figure 3.7 compares different percentages of dead nodes over the simulation time, and shows that nodes under VAR-RC have longer life.

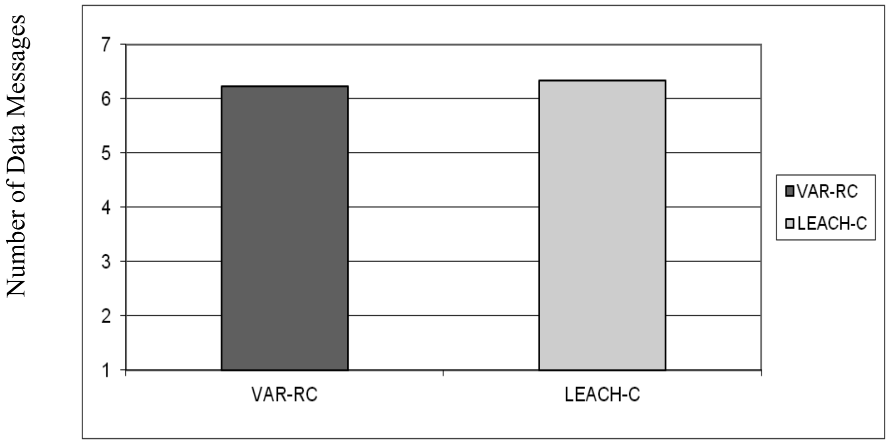

Figure 3.8 the number of the data messages received by the BS.

3.3 The Minimum Round Time Controller (MIN-RC)

A round time controller provides a dynamic technique that allows the BS to change the current round time according to the current network state. In section 2.5 the problem of uneven clustering was discussed, in which nodes belonging to small-sized clusters will perform more frames than those belonging to larger ones. This yields energy consumption diversity among different nodes, especially for cluster heads at locations farther from the BS, and this leads to significant energy inefficiency. In this section, another adaptive mechanism will be introduced called Minimum Round Time Controller (MIN-RC), in which the round time is dynamically adjusted considering the smallest cluster size.

Minimum Round Time Controller (MIN-RC) is motivated by the need to improve the network performance by reducing the uneven workload effects resulting from dynamic clustering. The major effect of employing fixed-time round in cluster based protocols is that the heads of small-sized clusters will be overloaded with more than the average workload, because the frame length, is short. Thus they perform more frames during the same period of time, therefore they will spend more energy sending less data compared to other heads in even clustering situations, and hence it needs to transmit more data packets to the BS, which requires the CH to increase their transmission power to avoid multipath fading. In addition to the different load problem, the death of the cluster head during the round will also affect the overall performance of the network. When a cluster head is no longer alive, nodes belonging to that cluster cannot determine whether the CH is alive or not; this will lead to a significant energy waste because nodes will continue sending their data till the round ends, or possibly the node itself dies.

The MIN-RC uses an adaptive technique to best utilise the available energy, and reduces the efficiency loss related to uneven load. The key idea of MIN-RC is to reduce the time of the operational phase, allowing the network to dynamically adapt to the present networks state.

According to the wide-range of cluster size, the number of frames to be done by clusters varies significantly during a round. The head of a cluster with fewer members needs to send more messages, although these messages represent fewer members' measures. Moreover, the members of such a cluster would have more frequent active modes, and yield more inefficient communication.

Despite the opposite view with many routing protocols, that is increasing the life time can be used in a manner that results in some detriment to the amount of the forwarded data, under different application requirements the amount of the delivered data messages is very important, therefore less data is considered as efficiency loss. This raises the question of whether more data or long lifetime is more important.

Assuming that the concern is with designing an energy efficient routing protocol, it is obvious that faster node death would likely be a disadvantage to the WSN. However, losing important or sensitive data causes failure to comply with the application's intended-goals and may result in losing the purpose of the design.

In view of these requirements (increasing the amount of the delivered data, network longevity), the MIN-RC protocol intends to ensure that the network complies with its design requirement to monitor and forward data, and how to spend the available amount of energy in line with the reasonable expectations of the longevity concerned.

3.3.1 The Protocol Operations

The system lifetime in MIN-RC is similar to VAR-RC. At the beginning of each round, sensor nodes start the setup phase, sending their information to the BS, which is required by the clustering algorithm waiting for the clustering information. Whenever the BS receives nodes' information, it maintains the current state of sensor node that is for a given sensor node- the sensor ID, location and the current energy level. Then the BS starts the clustering process by identifying the set of nodes that are eligible to act as clusters heads for the current round. A node is an eligible node if its current residual energy is above the average energy of all nodes. When the eligible cluster heads are identified, the simulated annealing algorithm is performed to elect k cluster heads from the eligible nodes set. The clustering algorithm ends by partitioning the nodes into k clusters, and identifying the head and members for each cluster for the current round. After obtaining the clustering information in addition to the predefined optimal clustering parameters (optimal cluster size, optimal round time) the BS calculates the operational phase length. Once the clustering information, in addition to the length of the operational phase is defined, the BS broadcasts this information to all nodes in the network and waits for the collected data from the clusters head. For all nodes, when a node receives the clustering information message, the node checks if it is a cluster head or not. If the node is a cluster head then it maintains a list of all nodes that belong to the its cluster, and changes to being awake, waiting for its member's data; otherwise, the node is a member node and it can determine its cluster head and its time slot in the TDMA schedule and the schedules in its active periods according to the length of time of the TDMA schedule and changes in its status to sleep mode, when the node schedule its active periods it should ensure that the cluster can finish a complete frame, therefore some clusters may have a no transmission period the end of the round, and the length of this period depends on the round length and the frame length, and this may lead to loss of sensitive readings . Then the operational phase starts as in VAR-RC.

3.3.2 The Modified Round Time

To define the length of the operational (steady state) phase, the minimum-size cluster (C_{min}) is considered as the base for identifying the operational period.

Now the calculation of the operational phase's length will be discussed in detail, assuming that:

- N: is the network size (the number of sensor nodes)
- K: is the desired number of clusters
- R_i: stands for the current round
- C_{ij} is the cluster j at the round i, where j: 1… K
- CH_{ij} is the cluster head of the cluster C_{ij}
- M_{ij} is the size of the cluster C_{ij}
- T: is the optimal round time

For the smallest cluster size (C_{min}) the number of cluster members is denoted by M_{min}, so the frame time for C_{min} can be defined as:

$$F_{min} = \sum_{m=1}^{M_{min}} \sigma + \lambda \tag{3.10}$$

where σ denotes the slot time assigned to the node, so that the node can send its obtained measure to its cluster head, and λ stands for the time required by the cluster head to complete the data aggregation and forwarding.

Assuming that the network consists of N nodes, divided into k clusters, so that the optimal number of frame ($N_{f\_average}$) can be obtained as mentioned in section 3.2, and the optimal round time (T) then the number of frames that can be completed by the cluster (C_{min}) can be defined as follows:

$$N_{f\_min} = T/F_{min} \tag{3.11}$$

Because of the small number of nodes in the cluster C_{min} the frame time becomes smaller, thus this will definitely increase the number of performed frames, and can lead to more energy inefficiency and speed up the node's death.

As mentioned earlier, the effect of excessive numbers of performed frames has a direct impact on the total amount of energy consumed by a cluster. Therefore, for fast recovery from such a situation, shrinking the operational phase can be a reasonable action for inefficient-state recovery.

To further minimise the number of messages for the overloaded CH, modifying the round time can help nodes belonging to the overloaded clusters to quickly recover the context. Despite VAR-RC, it is not necessary to modify the slot time, since it is not required to change the frame length and send data as much as possible; however, MIN-RC aims to update the round time without affecting the frame length.

Now the modified round can be calculated as follows:

$$T_{current} = N_{f\_average} * F_{min} \tag{3.12}$$

In this way, using the MIN-RC scheme, minimising the number of lost packets caused by the head's death during the round assures that the network will quickly adapt to the situation where some heads may die before completing the current round, and this will certainly reduce the number of lost packets caused by the death of the CH during the Round time.

3.3.3 Simulation of MIN-RC

This section illustrates the simulation results of the round time controller MIN-RC in order to show the effect of MIN-RC on network performance. In this experiment we conduct 5 trials for each protocol and the average the total delivered for all trails has been computed, that minimises the variance of the average is selected, and the same topology was used, and the same system parameters as used in section 3.2.2 (the simulation of VAR-RC).

From figure 3.9, it can be noted that MIN-RC improved the network performance and the total number of the delivered data messages has increased by about 7.3% compared to LEACH-C. Furthermore, figure 3.10 shows the average energy consumed to send a single data message to the BS. As all nodes start with the same energy level for all simulations, it is obvious that MIN-RC is better than LEACH-C in terms of energy utilisation and it can deliver more data with the same amount of energy.

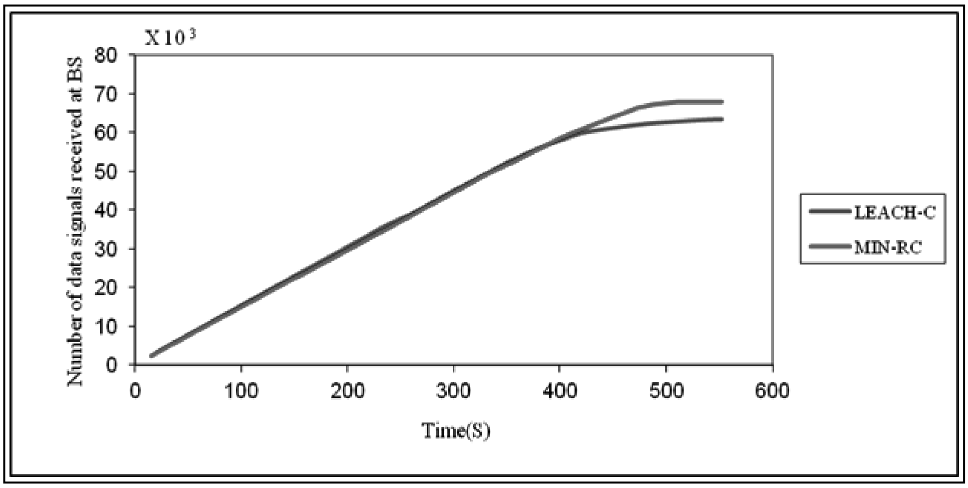

Figure 3.9 the number of delivered data messages by both protocols VAR-RC and LEACH-C over the simulation time.

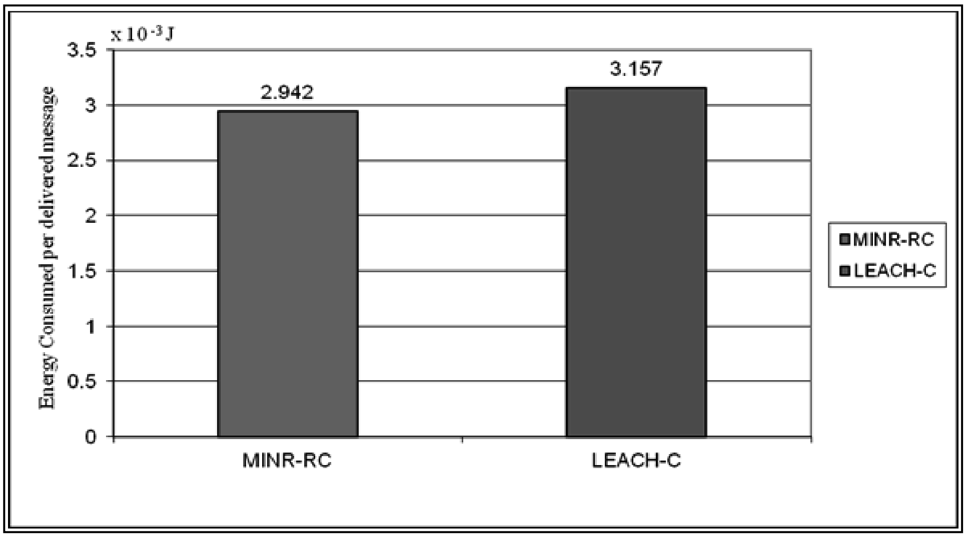

Figure 3.10 the average of the energy consumed per data message received at the BS shows that MIN-RC consumed less energy than LEACH-C.

Figure 3.11 illustrates the average of the received data messages over the time, and it can be noted that MIN-RC can keep a higher data rate after node death compared to LEACH-C, and it shows how quickly the number of deliveries decreases under LEACH-C after the death of the first node, while MIN-RC still has the ability to deliver relatively more data after the nodes start to die. This means that it has the ability to give a better image of the monitored phenomena.

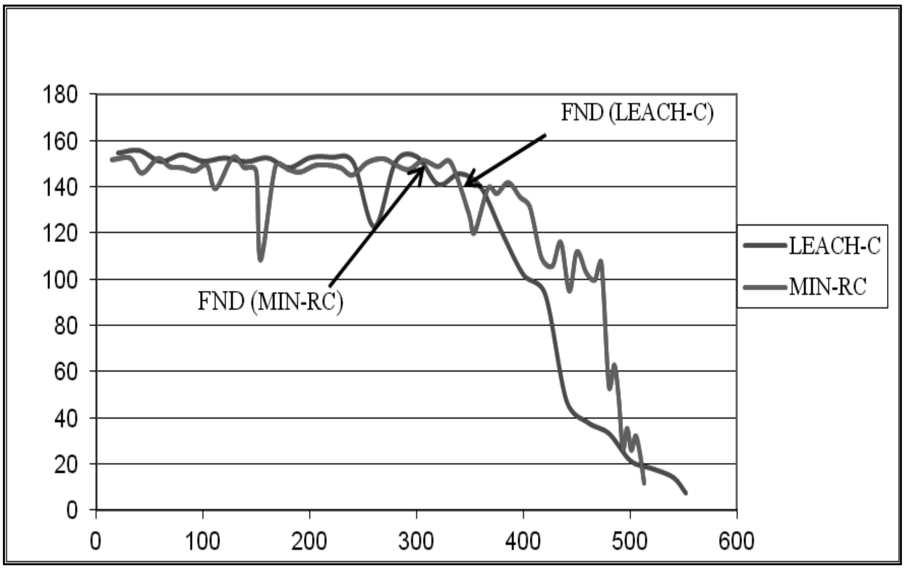

Fig 3.11 the average of the received messages over the time, with indication when the first node die of both MIN-RC and LEACH-C,

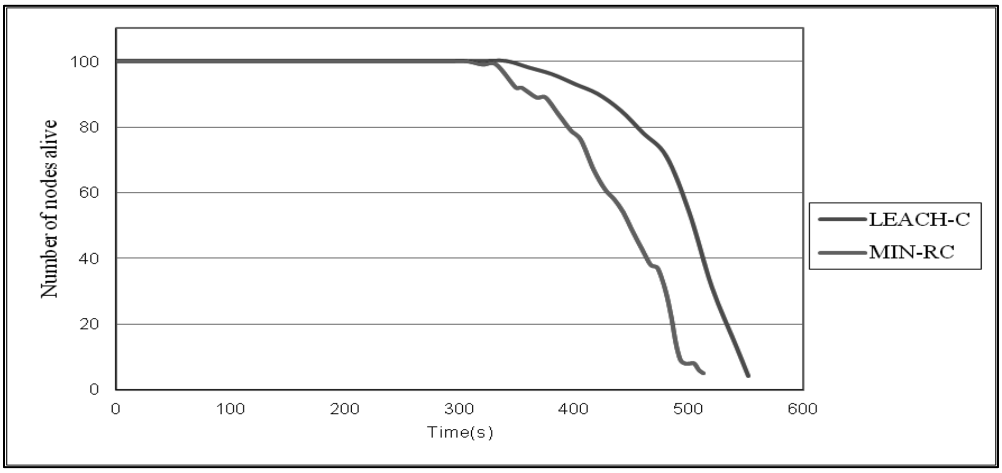

Figure 3.12 the number of nodes alive under LEACH-C and MIN-RC during the simulation time

Figure 3.12 compares the network lifetime for both MIN-RC and LEACH. Nodes under LEACH-C have a longer life span compared to MIN-RC; however, nodes in MINR-RC can send more data than LEACH-C within a smaller period of time compared to LEACH-C. This indicates that MIN-RC can deliver more data faster than LEACH-C, which makes it more suitable for certain applications.

3.4 Summary

In this chapter, the effectiveness of the round time controllers on the performance of the cluster-based wireless sensors networks has been presented, and this has been demonstrated through simulating how the variable round time can affect and improve network performance.

Two novels adaptive round time controller techniques (VAR-RC and MIN-RC) have been proposed and evaluated considering the cluster's size.

The adaptive round time controller provides a basis for controlling network behaviour according to the application needs considering the current network state. In other words, the user or the application itself can adapt the nodes' behaviour to achieve the desired performance, extending the network's lifespan or increasing the amount of data.

The proposed methods show that by adapting the round time, it would indeed result in significant improvements in the network's performance, and thus achieve optimized energy utilisation either for network longevity or the total amount of the delivered data.

CHAPTER 4

A Load Sharing Technique for Cluster-Based Wireless Sensor Networks

4.1 Introduction

Typical dynamic clustering protocols in WSN suffer from the unfairness of load distribution among cluster heads, and the fairness of load distribution is an important requirement in designing a hierarchal routing protocol. An example of such an unfair situation is that the clusters are created with different sizes and some cluster heads may be located at farther locations from the sink. This unfairness would result in an imbalance of energy consumption and therefore affects the overall network performance. In the previous chapter, two adaptive round time controllers have been introduced in order to reduce the effects of an imbalanced workload on cluster heads; while in this chapter the aim is to introduce another dynamic technique called a **Co-Cluster Head,** which aims to assign a part of the cluster head workload to one of its members to ensure fairness and reduce the imbalance in energy consumption.

4.2 Intra-Cluster Cooperation

The cluster-based WSN is considered a dynamic interactive process between the cluster head and the cluster's members, an environmental phenomenon and the end user. This interaction process has to be managed in order to provide the structure and predictability that are necessary to satisfy the intended application's requirements, while considering the limited capabilities of the sensor node, where the limited energy source is the main principle.

The typical data transmission in cluster-based WSN is achieved by sending the sensor's data to a far away sink or BS through a cluster head. The cluster head nodes are concerned with data aggregation and forward the aggregated data directly (or possibly through multi-hop) to the BS; therefore, the cluster head task consumes most energy, which in turn speeds up their battery depletion and consequently affects the overall network performance. Therefore, enhancing the cooperation among nodes by sharing the most energy consuming task among nodes and changing nodes' roles periodically can reduce the rate of death of the head node and assures fairness among nodes. Even so, using this method the fair distribution problem still exists, especially in dynamic clustering where some cluster heads may be assigned more workload than others or some of them may be located at farther locations. Therefore, they may not spend an equal amount of energy during the same round.

The principal idea of the Co-Cluster Head technique is to enhance the cooperation process among nodes during the same round in order to minimise the effects of unfair distribution of the workload. In particular, ensuring a cluster head which has been assigned an extra workload or is unable to complete the round is willing to share some of its load with one of its members in order to save more energy and reduce the faster depletion of its battery is important.

The Overload Problem

The energy consumption during the round is influenced by the number of frames to be performed, the number of received messages by the cluster head and the location of the cluster head, thus the extra load that has been assigned to some heads would indeed affect the amount of energy consumed by a cluster head during the round, and can lead to inefficiencies and unfairness among nodes, resulting in inefficient overall network performance.

For a network consisting of N nodes and the network already partitioned to k clusters as discussed in the previous chapters, assuming that we have a cluster C with N/k members, the distance from the CH of C to the BS is d_{avg}, which is the average distance from all nodes in the network to the BS, $(\sum_{i=1}^{N} d_{i\_toBS})\ /N$.Then it is possible to compute the average energy consumed to complete a single frame by the cluster head (E_{CH}) as follows:

$$E_{CH} = lE_{elec}\left(\frac{N}{k}-1\right)+lE_{DA}\frac{N}{k}+l\,\varepsilon_{mp}d_{avg}^{4} \tag{4.1}$$

Where l the signal length, E_{DA} is the amount of energy used for data aggregation, $\in_{mp}$ the required energy amplifier to avoid multipath fading. And the total energy consumed by this cluster head during the round to complete the average number of frames $N_{f\_average}$

$$E_{avg} = E_{CH} * N_{f\_average} \tag{4.2}$$

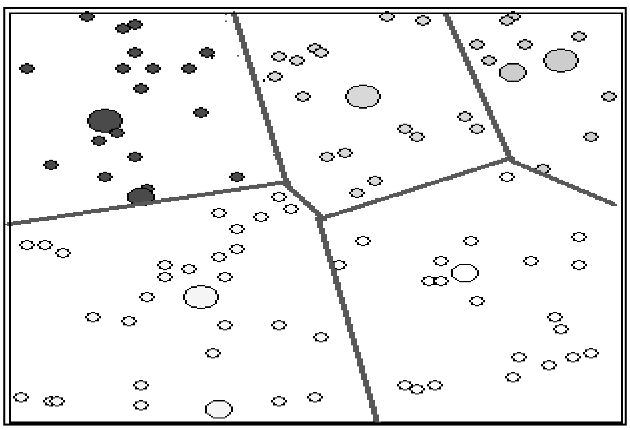

Figure 4.1 The nodes distribution, shows the variance of the clusters ‘sizes

However, this is not the case in dynamic clustering, since dynamic clustering exhibits a large variety of cluster sizes. Figure 4.1 illustrates the variance in the cluster sizes at round i, therefore any cluster head that is expected to spend more energy than the average energy or the CH cannot complete the round because its energy level is less than the required amount to complete the round. Then the CH should be willing to share some of its workload with another cluster member to avoid faster depletion of its battery.

4.3 Choosing the Co-Cluster Head (CCH)

The question here is how to choose the CCH and what is the amount of load to be assigned to the elected CCH?

To choose a CCH from the cluster members, at first the candidate set X that contains all nodes that belong to the cluster will be defined, except of course the head of this cluster $X = \{ x_1, x_2, \ldots, x_m \}$,and electing one member from the candidate set will ensure that the energy level of the elected node after the round completion does not fall below the energy level of the original CH, otherwise a faster node death problem may be faced.

As mentioned earlier, the set of candidate nodes X contains all cluster members that are able to share some of the head's load, however only one of these candidates is to be elected as CCH for the current round. Therefore, two different selection schemes are employed in order to determine which of these candidates should act as CCH for the current round. The first selection scheme applied is based on selecting the node that has the minimum intra-cluster communication cost, referred to as Min-Cost, while in the second selection scheme Max-Energy, the candidate with the highest energy level, is selected as CCH for the current round.

4.3.1 Minimising the Intra-Cluster Cost

The candidate node with the minimum intra-cluster communication cost will be selected as CCH in order to minimise the intra cluster communication overhead which may results from assigning the role of the CH to CCH. The communication cost is the sum of the difference of the squared distance from any node to the CCH and CH respectively, and can be defined as follows:

$$Minimize\ f(x)\ ,x \in X\ and\ x \neq CH$$

$$f(x) = \sum_{m=1}^{M_i} d^2_{\{m,CH\}} - d^2_{\{m,x\}} \tag{4.3}$$

Where $d_{\{m,CH\}}$ is the distance from the cluster member m to its CH is, $d_{\{m,x\}}$ is the distance between the cluster member m to the candidate CCH.

Subject to:

$$E_{current}(x) - p * E_{round}(x) >= E_{current}(CH) - (1-p) * E_{round}(CH)$$

Where $E_{current}$ is the current energy level of the node, E_{round} the expected energy consumption by the node during the round and p is the load sharing percentage. The above condition ensures that the energy level of the selected CCH will not fall below the energy level of the original CH after it has been assigned the part of load p.

4.3.2 Choosing the Node with Maximum Energy

An alternative scheme for choosing the CCH from the candidate set X is to choose the node that has the maximum level of residual energy. This ensures that after completing the round the CCH would have an amount of energy that enables it to live more.

To formulate the selection function f(x):

$Maximize\ f(x)\ ,x \in X\ and\ x \neq CH$

$$f(x) = E_{current} - p * E(x) * N_f$$

Subject to: (4.4)

$$E_{current}(x) - p * E_{round}(x) >= E_{current}(CH) - (1-p) * E_{round}(CH)$$

Where p is the percentage of the shared load, *E(x)* is the amount of the energy needed by candidate x to complete a single frame, and *NF* is the total number of frames to performed by the cluster during the current round.

4.4 The Co-Cluster Head Protocol Operations

The operation of the Co-Cluster Head protocol follows a similar approach used by LEACH-C, as discussed in chapter 2. The network lifetime is broken down into a set fixed length periods (rounds), and each round consists of two phases the setup phase (cluster formation) and the operational phase (data gathering phase).

The Setup Phase nodes start the setup phase by sending their information (Id, location, current residual energy) that is required by the clustering algorithm-*changing the criteria used for selecting the CH*. Once the BS receives the nodes' information it defines the set of eligible nodes that can be selected as cluster heads for the current round, and a node is eligible if its residual energy level is greater or equal to the average residual energy of all nodes. In addition another condition is added for defining eligibility, which is that the node must not have been a cluster head in the previous (N/k – 1) rounds to assure fairness in giving all nodes the same opportunity to be elected once every N/k round. Then the BS partitions the network into the desired number of clusters and applies the simulated annealing algorithm, after clusters have been identified. Then BS calculates the expected amount of energy that each head may consume during the next round. As a result, it can determine whether the head is willing to share some of its load or not; if so, then the BS will start the CCH selection process discussed in section 4.3. By the end of the setup phase, the BS sends the clustering information in addition to the CCH for each cluster (if applied) to all nodes in the network.

Once the node receives the clustering information, it can determine if the cluster has a CCH or not, since the intra-cluster communication process will depend on whether the cluster has one or not.

4.4.1 The Cluster with a Co-Cluster head

All nodes belonging to a cluster that has a CCH would calculate T_{change}, which is the time when the CCH will assign the CH's task, because the round consists of a set of integral frames, with frame length F, and if the CCH will assign p, the percentage of the head's load, then the CCH will start acting as a CH just after the head completes (*1-p*) the total number of frames NF. Thus, the time to change T_{change} can be computed as follows:

$$T_{change} = T_{current} + (1 - p) * N_f * F \tag{4.5}$$

4.4.2 The Operational Phase

In the operational phase or data gathering stage involves each node starting to send its readings to the corresponding cluster head.

In typical hierarchical protocols, the term *intra-cluster communication* in this context implies that once the clusters have been identified, any member node is connected to only one cluster head at the beginning of each round, and the data transfer is achieved by sending members' data to the BS through the cluster head until the current round ends.

While in CCH-protocol for clusters that have a CCH for the current round, the CH will change dynamically at the time (T_{change}) and the CCH will be assigned CH task, so that all nodes belonging to the cluster will automatically maintain their connections to respond to the CH's reassignment, and the data transfer is achieved through the new cluster head. When the CH and CCH exchange their roles, as illustrated in figure 4.2, all other cluster members will set their CH parameters to point to the new cluster head, which in this case is the CCH. Then the CCH cluster head will change its state to wake up until the round ends, in order to be able to receive data from all members, including the old cluster head. Also, the old CH will maintain its state of being a normal member and goes to sleep waiting for its time slot to send data to the new CH.

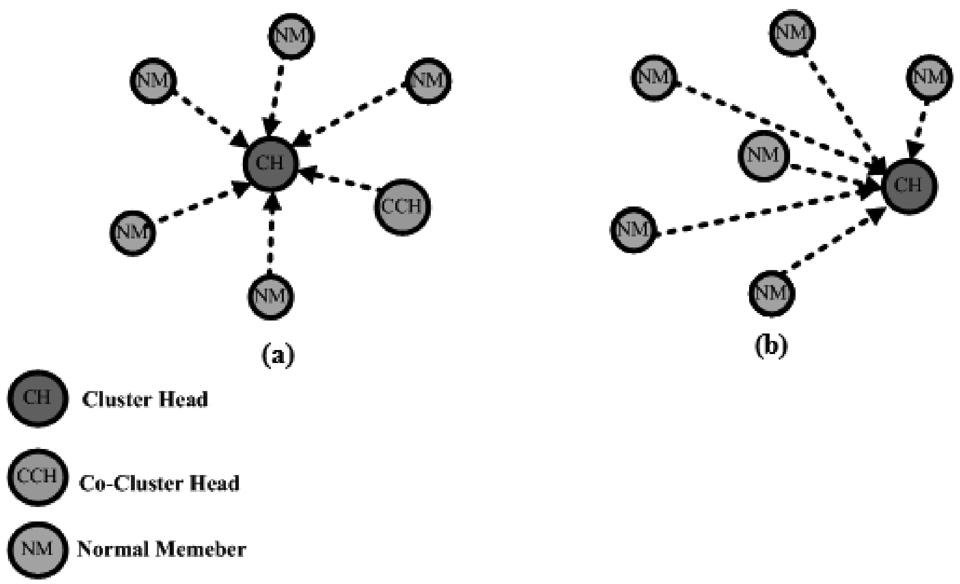

Figure 4.2.a the data transfer at beginning of the round ,nodes send data to the cluster head , b) after the time to change *Tchange* the CCH takes the responsibility as CH , other nodes including the old CH start reporting their readings to the new CH.

4.5 Simulation of Co-Cluster Head Protocol

A simulation has been conducted to show the effectiveness of using the CCH protocol in cluster based WSN. As mentioned earlier in this chapter, the basic idea of the CCH protocol is to improve the intra-cluster cooperation by assigning a part of the CH's load to a selected cluster-member called CCH. Two techniques have been considered for selecting the CCH, the first one based on selecting the node that minimises the intra-cluster communication cost, while the second one considers the node with maximum energy level.

The simulation experiments in this chapter are designed to investigate the efficiency of the Co-Cluster Head protocol, and different values for the percentage of the shared load (p) have been tested to show its effect on the overall network's performance, and we conduct 5 trials for each protocol and the average the total delivered for all trails has been computed, that minimises the variance of the average is selected.

Before starting to compare the Co-Cluster Head protocol to LEACH-C in terms of the number of dead nodes and the amount of data delivered, let us explain the behaviour of the network model under consideration. In the network model it is assumed that each sensor always has data to send, so that the ideal behaviour of the network is that all nodes will send the same amount of data, and at a certain time all nodes would spend the same amount of energy and they will die at that time. However, the network would not follow this ideal behaviour because of different factors that affect the network's behaviour such as the cluster size, the intra-cluster communication costs, and the location of the cluster head. So to identify the best performance of LEACH-C, considering the network topology and the values of simulation parameters, the average number of rounds R_{avg} has been computed first. Before the death of any node from the LEACH-C protocol, the average round cost R_{cost} and average number of messages per round R_{msg}, have been computed by dividing the initial amount of energy by the average round cost (200/ R_{cost}), to obtain the average number of rounds $R_{avg,}$ which is about 24 rounds or 480 seconds, and the average number of data messages per round R_{msg} is about 2986. As a consequence, the expected network lifetime is 480 seconds, and all nodes will die at this time and the expected amount of delivered data messages (R_{avg} *R_{msg}) is about 71664; however, LEACH-C did not follow this pattern in the following rounds since some nodes started to die and the overall network performance changes accordingly. Therefore, when comparing the performance of both protocols, the expected network life time and the expected amount of data delivered should be considered.

4.5.1 The Simulation of the CCH with the Min Communication Cost

A simulation is designed to investigate the potential intra-cluster cooperation. Considering the intra-cluster communication cost for choosing the CCH, this section will investigate the performance of the Co-Cluster Head with the percentage of the shared load equals to 40% (*p=0.4*), as it shows the best performance in terms of the amount of data received by the station. Also, a detailed comparison for different values of *p* will be discussed in section 4.2. A comparison of the network's efficiency in terms of the total amount of received data messages over the simulation time is shown in Figure 4.3. It should be made clear that under the CCH-protocol, the number of received data messages by the BS is much greater than that of the conventional LEACH-C, since the CCH-protocol can deliver about 6.4% more data than the conventional LEACH-C protocol consuming the same amount of energy.

Furthermore, to illustrate the benefit of having a CCH, the amount of data delivered per round has been compared.

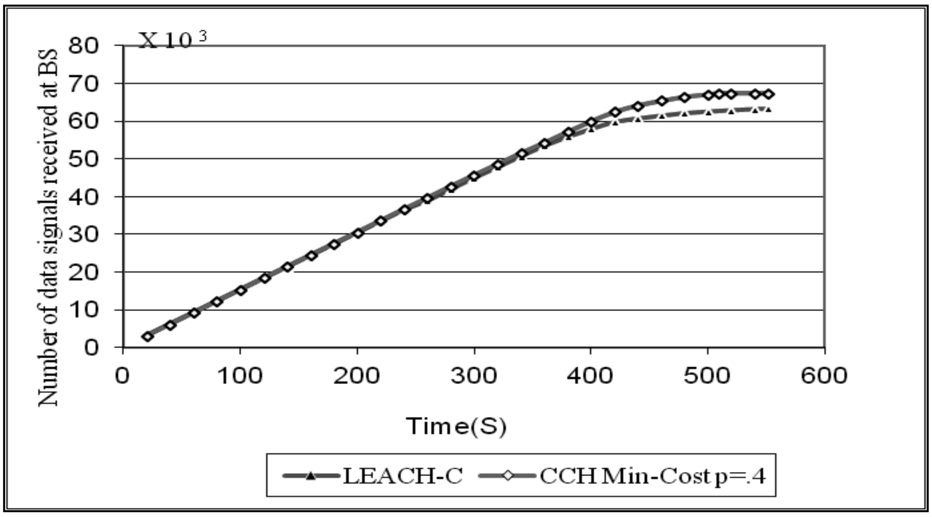

Figure 4.3 the total number of data messages received at the BS over the simulation time, the shred load percentage p=.4 and CCH is chosen using the minimum cost selection scheme.

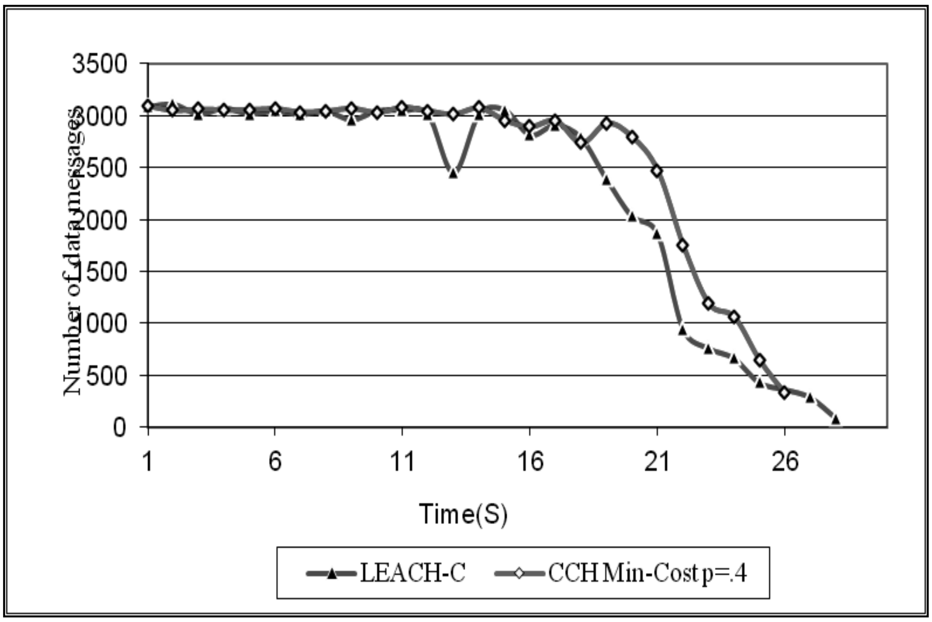

Figure 4.4 the number of the delivered data messages per round , the shred load percentage p=.4 and CCH is chosen using the minimum cost selection scheme.

From the results shown in figure 4.4, it can be clearly noted that both protocols delivered relatively similar amounts of data during the periods from the beginning of the simulation until the death of the first node, and the difference between both protocols is quite small. However, as nodes start to die, the number of data messages delivered by LEACH-C quickly declines. This decrease is a consequence of the CH's death during the round, because once the CH died, the entire cluster concerned is unable to send any more data until the round ends. On the other hand, under the Co-Cluster protocol when the head died, there is still an opportunity to recover such a situation, since the CCH will be assigned the CH task at a certain time (depending on the value of p) during the round, thereby minimising or maybe avoiding the data loss caused by the CH death. Even so, using CCH may not completely avoid the whole of this data loss, because the amount of this loss depends on the length of time between the CH death and the time when the CCH starts acting as a cluster head. For example, assume that the CH died at time t_1, and t_2 is the time when the CCH assigned the CH's task, then if t_2 is greater than t_1 , all of the data sent by the cluster members during the time period Δt ($\Delta t = t_2 - t_1$) will be lost. Further potential data loss results when CCH dies at a certain time, for example t_3 that is greater than t_2, therefore all the measured data between t_3 till the round ends will be lost.

4.5.2 The Simulation of the CCH with the Maximum Energy Level

This simulation is designed to investigate the effect of using the CCH protocol selecting the CCH based on the node's current residual energy level.

For this simulation it has been assumed that the value of p is 0.5, since it shows the best performance in terms of the number of data messages delivered during the round. Also, the results of using different values for p will be discussed later in this chapter. Figure 4.5 illustrates the total amount of the received data over the simulation time. This figure shows clearly that the CCH protocol has a significant improvement in sending data over LEACH-C, making better use of the available amount of energy, since all nodes start the simulation with the same initial energy level.

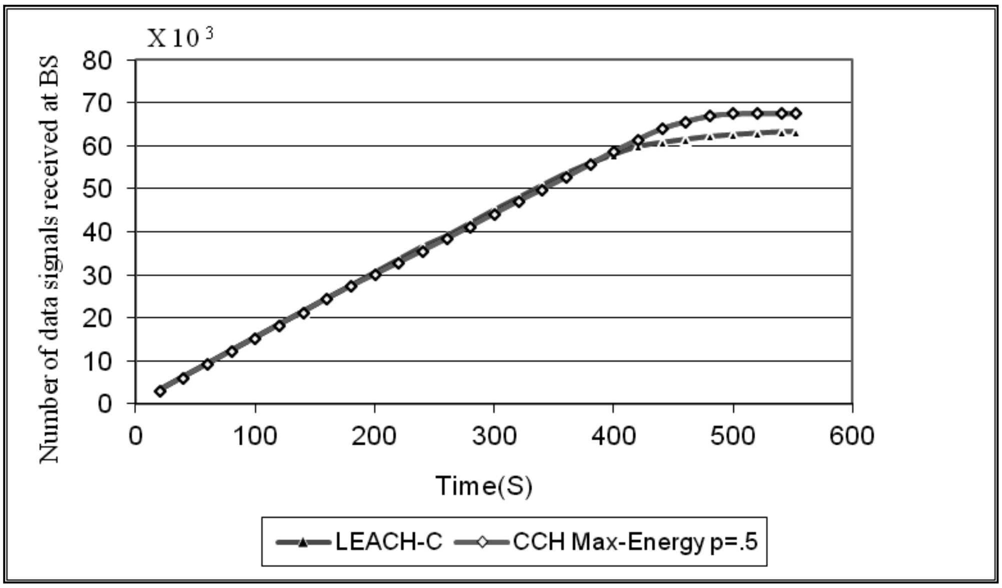

Figure 4.5 the number of the delivered data messages over the simulation time. The shared load is p=.5 and CCH is chosen using the Max-Energy selection scheme.

Figure 4.6 plots the amount of received data over rounds, and figure 4.8 plots the number of data messages per round with the number of nodes alive per round; the percentage of the shared load is set 50%(p=0.5). From those figures, it can be seen that under LEACH-C the amount of data received drops quickly when nodes start to die, where the first node died during round 18, although the first node died during the round 16 under the Co-Cluster Head protocol. However, it continues sending more data compared to LEACH-C for most of the simulation time, then the amount of data decrease in later rounds after round 24. Even so, this decrease does not have a significant effect on overall performance because most of the nodes have died, and consequently the amount of data received from the protocols is very small and constitutes about 0.009% of the total received data, since the protocol has delivered most of the data at an earlier time compared to LEACH-C, while the percentage of data that is delivered by LEACH-C during the latest rounds is about 0.019%.

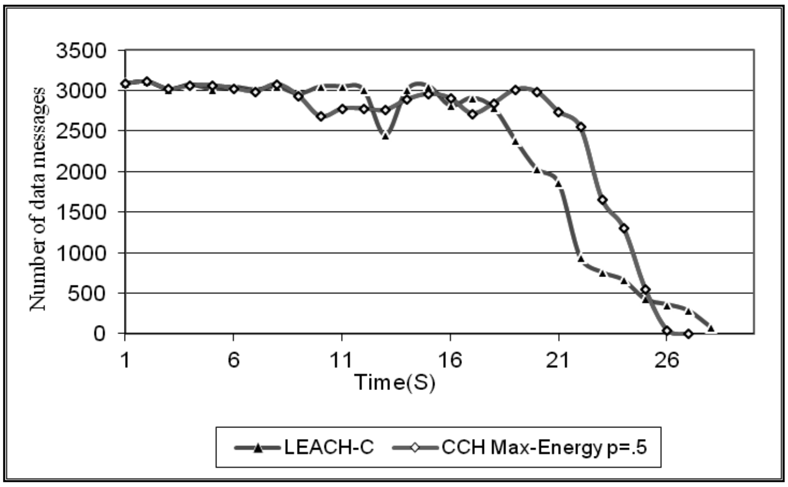

Figure 4.6 the number of the data messages per round, the CCH with p=.5 and CCH is chosen using the Max-Energy selection scheme.

To compare energy efficiency, the average energy consumed per message delivered has been compared by dividing the total initial energy by the total of received data messages. From figure 4.9 it can be seen that the CCH can best utilise the available amount energy and reduces the average power cost for sending a single data message for both selection schemes. Moreover the results shows that the max-energy with p=0.5 shows the best balanced of the energy consumption among nodes, and this can be seen from figure 4.7

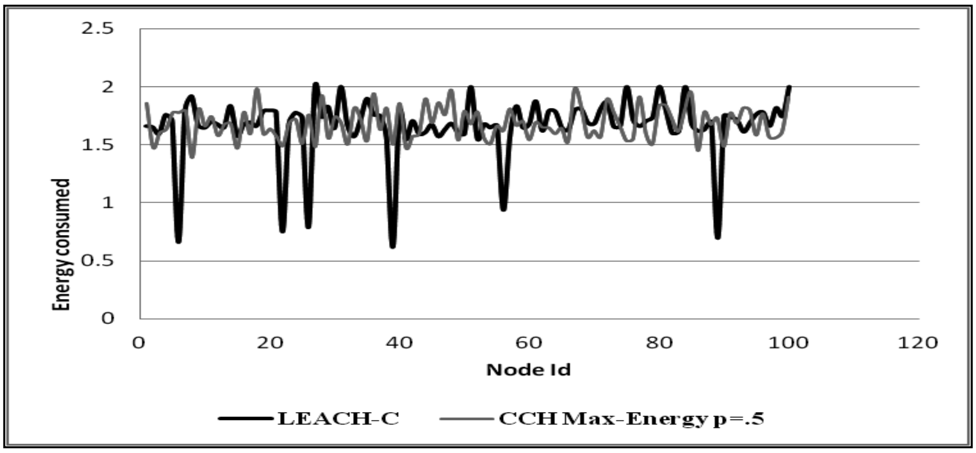

Figure 4.7 the energy consumed by each node at the end of round 20.

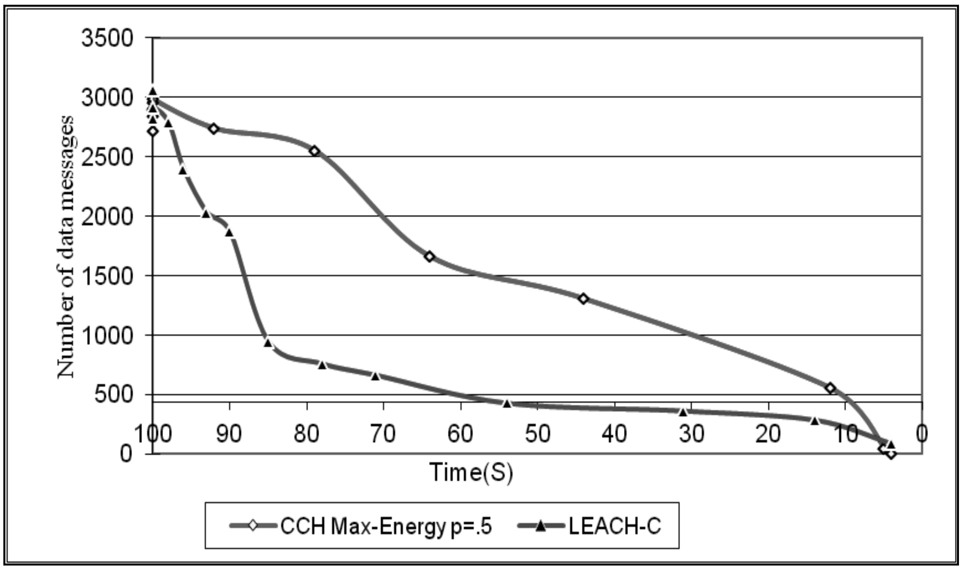

Figure 4.8 The number of the delivered data messages per round with the number of nodes alive per round for the region of interest from round 15 till the last round for both protocols, the simulation of the CCH protocol ends during round 26, while LEACH-C ends during the round 29.

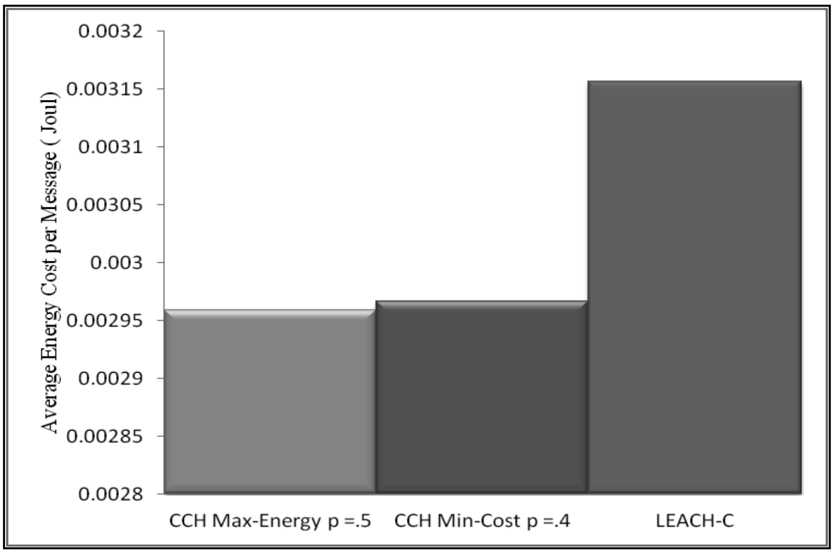

Figure 4.9 the average energy cost per data message received by the BS, with p=0.4 for the CCH with Min-Cost selection scheme and with p=0.5for the Max-energy selection scheme.

4.5.3 Simulation of both CCH Selection Schemes with Different Shared Loads

To study how the value of p can affect the overall network performance of the Co-Cluster Head protocol for both selection schemes, the simulation was designed to investigate the performance of having a CCH for different shared load percentages (p=0.1, 0.2, 0.3, 0.4 and 0.5).

As mentioned earlier in chapter 3, to compare the Co-Cluster Head protocol to LEACH-C from the point of view of nodes' death or the number of nodes alive over time, different metrics can be used to evaluate the network life[98], such as the time when the first node dies (FND), half of the nodes die (HND) or when the last node dies (LND). To study the effect of using CCH for the number of dead nodes, considering the above life metrics, table 4.1 compares the times for FND, HND and 95%ND, since it is assumed that the simulation ends when the number of nodes alive is less than or equal to the number of clusters.

The simulation results shows that under LEACH-C the first node died at 350, and half of nodes and 95% of nodes died at 502,551 respectively. From table 4.1 it can be seen that the use of p=0.1 for both CCH selection schemes shows the best improvement at about 5% over LEACH-C. Moreover, it results in better performance in sending more messages compared to LEACH-C; however, this improvement is less significant compared to other values of p. While for other values of p, the results show that the first node dies earlier. Because different reasons may speed up the death of some nodes, the amount of load that has been assigned to this during the previous rounds, or for example if the node has been assigned CCH task, as it is big, and then assigned CH task but without sharing its load with a CCH.

To compare LEACH-C with the proposed CCH protocol in terms of HND and LND, the comparison should be made in view of the expected network life time and the amount of the delivered messages. This means that the best performance of the network is when the death of the half nodes or all nodes is very close to 480 (the end of round 24), and the amount of data delivered is maximised.

It can be seen from table 4.2 that the time when half of the nodes die is 474 when choosing the maximum energy selection scheme with p=0.5, which is very close to the expected time 480; while under LEACH-C, half of the nodes died at 502. Comparing the amount of data delivered when half of the nodes die shows that CCH has a significant improvement in the amount of delivered data messages at about 6% compared to the amount of data delivered by LEACH-C. To be more specific, the amount of delivered data from both protocols has been compared at the time of 480, and the results show that the improvement of CCH over LEACH-C is 7.7%. Moreover, this amount of data constitutes 99.1% of the total number of messages delivered by the protocol.

Table 4.1 the network life time in term of FND, HND

p	CCH Selection Scheme	FND	HND	95%ND
0.1	Max-Energy	366	486	544
	Min-Cost	369	486	540
0.2	Max-Energy	339	478	533
	Min-Cost	278	464	540
0.3	Max-Energy	346	473	520
	Min-Cost	343	462	502
0.4	Max-Energy	239	477	513
	Min-Cost	299	455	509
0.5	Max-Energy	405	474	521
	Min-Cost	264	474	520

For the min-cost selection scheme, the closest time when HND is 474 is with p=0.5 and the improvement over LEACH-C is 4.5%, and when comparing the amount of the delivered data at 480, the improvement is about 5% while this constitutes 98.7% of the total amount of data sent by the protocol.

To sum up, selecting the CCH based max-energy selection scheme, by sharing 50% of the CH's load, shows the best performance results. Furthermore, standard deviation for the amount of energy consumed by each node has been computed, at the round N/k that is 20. Figure 4.10 illustrates the standard deviation of the energy consumed of all nodes. It can be noted that CCH under the above assumptions has the minimum value of the standard deviation except for the Min-Cost scheme with p=0.2, which means it is better at balancing energy consumption over time, as well as sending the greatest number of data messages.

Table 4.2 The number of delivered data messages when the last node die LND

P	CCH selection Scheme	Number of delivered Messages	Improvement Over LEACH-C
0.1	Max-Energy	64077	1.86%
	Min-Cost	63660	1.2%
0.2	Max-Energy	64392	2.36%
	Min-Cost	63124	0.04%
0.3	Max-Energy	65548	4.2%
	Min-Cost	65378	3.94%
0.4	Max-Energy	66328	5.45%
	Min-Cost	65200	3.65%
0.5	Max-Energy	66709	6.05%
	Min-Cost	65703	4.45%

Table 4.3 The number of delivered data messages when half of nodes die LND(95%ND)

P	CCH selection Scheme	Number of delivered Messages	Improvement Over LEACH-C
0.1	Max-Energy	65094	2.73%
	Min-Cost	64973	2.54%
0.2	Max-Energy	66045	4.23%
	Min-Cost	65493	3.36%
0.3	Max-Energy	66866	5.52%
	Min-Cost	67012	5.75%
0.4	Max-Energy	66999	5.74%
	Min-Cost	67422	6.4%
0.5	Max-Energy	67591	6.67%
	Min-Cost	66617	5.1%

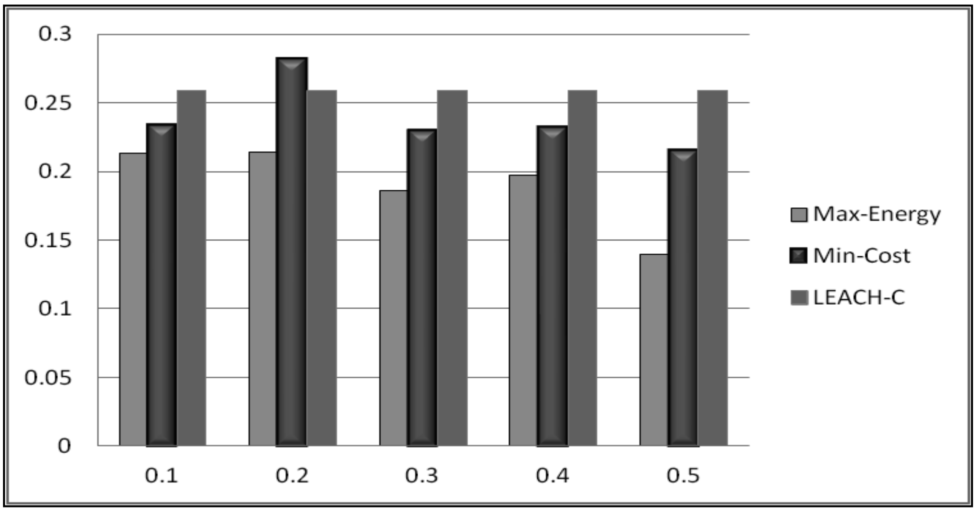

Figure 4.10 the standard deviation of the energy consumed by each round at the end of round 20., for both selection schemes of the CCH with p=0.1,0.2,0.3,0.4,0.5.

To conclude, for both selection schemes with different values for p, the CCH shows better performance in terms of HND, as nodes died at times close to the expected time, and it can deliver more data compared to LEACH-C; the percentages of improvement ranges from .04% to 6% depending on the CCH selection scheme and value of p. In addition when comparing the amount of data delivered at the end of round 24, the improvement ranges from 2.4% to 7%.

Now the CCH protocol will be compared to LEACH-C in terms of when the last node dies, that is when 95% of nodes die. From tables 4.1 and 4.3 it can be seen that applying the max-Energy selection method with p=0.5 shows that 95% of nodes died at time 513 which is the closest time to 480, whereas under LEACH-C, nodes died at time 551, and the improvement of CCH in the total amount of data is 6.67%.

Finally, the overall network performance will be compared with regard to the total number of delivered data messages at the end of the network life time, without considering the time when the simulation ends. The results from table 4.3 show that for CCH both selection schemes for all values of p results reveal better energy usage and send more data messages than LEACH-C. Max-Energy selection method with p=0.5 results in the best performance in terms of the number of delivered data messages when the simulation ends, compared to other values of p and the other selection scheme, and it outstrips LEACH-C by about 6.67%.

4.6 Summary

The very fact that WSN is a dynamic interaction leads to the need for effective cooperation within both inter and intra cluster communication. In this chapter it has been proposed that the co-cluster head protocol should aim to enhance the intra-cluster cooperation in order to reduce the effect of unfairness caused by dynamic clustering. To achieve this goal, the proposed protocol assigns a part of the CH's load to one of the cluster members referred to as CCH; in addition, having a CCH can avoid data loss resulting from the head's death during the round.

In order to choose the CCH, two selection schemes have been used the Min-Cost, and the Max-Energy. The performance of the CCH protocol has been evaluated through extensive simulation for both the CCH selection schemes with different load percentages. The results show significant improvements for both selection schemes in both the network lifetime and the number of data messages sent by the protocol compared to LEACH-C. However, using a predefined shared load percentage results different effect on the network's performance, which raises the need for more improvements to the protocol by using an adaptive method to identify the percentage of the shared load. In addition, different clusters may have different shared load percentages depending on the current network's state.

CHAPTER 5

Hybrid Protocol for Various Application Requirements

5.1 Introduction

In chapter 3 two different adaptive round time controllers (MIN-RC, VAR-RC) have been proposed as a basis for controlling the round time to adapt the current status of the network. The minimum round time controller technique (MIN-RC) was designed to provide both recoveries from unbalanced clustering to reduce the amount of energy waste with small sized clusters reducing the round length for faster recovery, of course without affecting the total amount of data sent over time, and the death of the CH during the round. The variable round time controller (VAR-RC) was designed to adapt the unbalanced clustering by increasing the round length to balance the number of accomplished frames during the round, so that when increasing the round time the largest sized cluster can perform the average number of frames. On the other hand, a small-sized cluster can adopt a modified slot to increase their frame length and carry out the same number of frames as the largest sized cluster. It is concluded that these two round time controllers provide a trade-off between the amount of data delivered and the network lifetime. In this chapter the aim is to obtain the benefits from both principles by introducing a novel round controller that the enables the user or the BS to adjust the network's behaviour according to the current network's state. It will adapt to different performance requirements (data-aggregation delay and lifetime longevity), and it will be shown how this novel method can be used to best utilise the energy budget.

5.2 The Protocol Basics

Hybrid protocol with round time controller(H-RC) is a centralised cluster-based routing protocol that aims to improve network performance by using variable length rounds supporting different traffic patterns and traffic dynamics in order to compromise between energy saving and prolonging the network lifetime. H-RC can support both high and low data aggregation delay requirements by changing the network behaviour to achieve the required aggregation delay level.

The case will be considered when variable aggregation delay levels are allowed during the network lifetime. An application dependent relaxing *value (RV)* α has been used to denote the required delay level for the current round, $1 \leq \alpha \leq L$, where L is the maximum aggregation delay level, and *The Relaxing Function (RF)* is used for generating the values of α.

When the aggregation delay level is 1, in such situation sensors are required to send as much as possible of their current data measurements, because as assumed earlier, sensors always have data to send. In this way, the H-RC follows the behaviour of MIN-RC**.** Otherwise, under higher aggregation delay level requirements, H-RC changes the network's behaviour by stretching the round length by following the principles of the VAR-RC, where each node adopts larger sleeping periods. However, in H-RC, rather than considering the largest sized cluster, the round length is extended by a relaxing value α.

Depending on the current network state, H-RC responses range from dealing with low traffic requirements, in which reports are delayed, to full-scale in which sensors report their data as in MIN-RC. The round length in H-RC will be changed to adapt to the required level of aggregation delay.

During the setup phase of the current round and in response to the change in the data obtained from the clusters in the previous round(s), and depending on how significant the change is, the relaxing function can anticipate the future behaviour of the network and compute the relaxing value α accordingly. When the new value of α has been determined, the current round length is a magnitude, and by the end of the setup phase, nodes will have the clustering information, the current round length, as well the relaxing value α, and they can adjust their sleeping pattern accordingly.

5.2.1 The Relaxing Function

The round time in H-RC is defined by considering the minimum cluster size as in MIN-RC, and the relaxing function is used to generate the relaxing value α for the current round, so that the round length is increased by α as in figure 5.1, while maintaining sending the same amount of data during the round. In other words, increasing the latency between any two active states of any cluster member to decide when the monitored data should be forwarded, as illustrated in figure 5.2.

In this way, when the value of α is high, H-RC allows sensors to utilise long sleeping periods to conserve more energy, and hence improve the network's lifetime longevity. While if the value of α decreases, sensors will adopt smaller sleeping periods, reporting more data during shorter time periods to meet the required latency level.

Having different round lengths as well as modified slots will lead to different delays in performance, although nodes will send the same amount of data as in MIN-RC with the same energy efficiency.

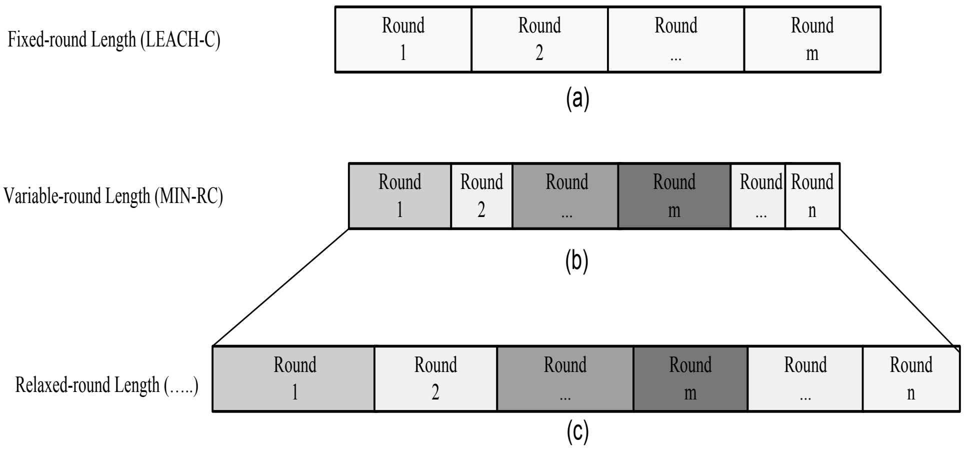

Figure 5.1 Original rounds length is computed as in MIN-RC , and the relaxed round after applying the relaxing α .

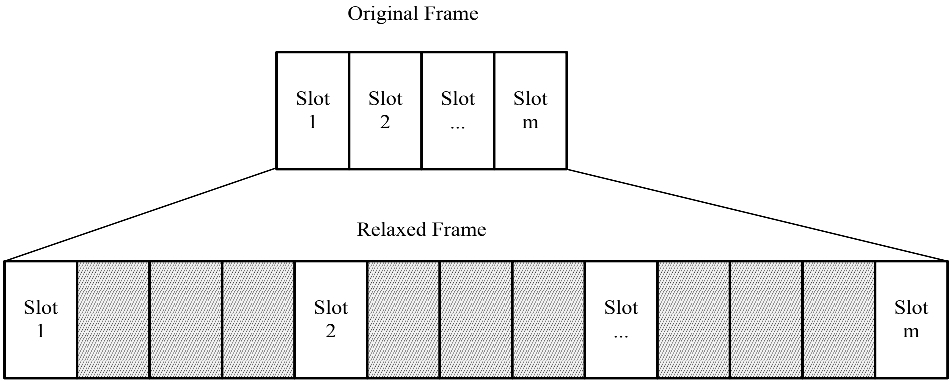

Figure 5.2 the relaxed frame after applying the relaxing value α=4 on a cluster with *m* members the numbered slots represents the active period for each cluster member to its data to the CH, and the shaded slots represents the free slots .

The relaxing function is responsible for identifying the value of the relaxing value α; therefore, under different application requirements, different methods can be used for computing the value for α, such as statistical and heuristic approaches, considering the current and previous data reports. In this chapter, the focus is on the effect of using the relaxed rounds scheme rather than the implementation of the relaxing function or how to compute the relaxing value.

5.3 The Protocol Operations

The typical protocol behaviour is similar to MIN-RC. Figure 5.3 illustrates a block diagram of the H-RC operations during the round, that is, the sensor node senses its surrounding environment continuously and uses its time slot in the transmission schedule to send the sensed data to its cluster head, and then switches to sleep mode state while waiting for its next transmission slot.

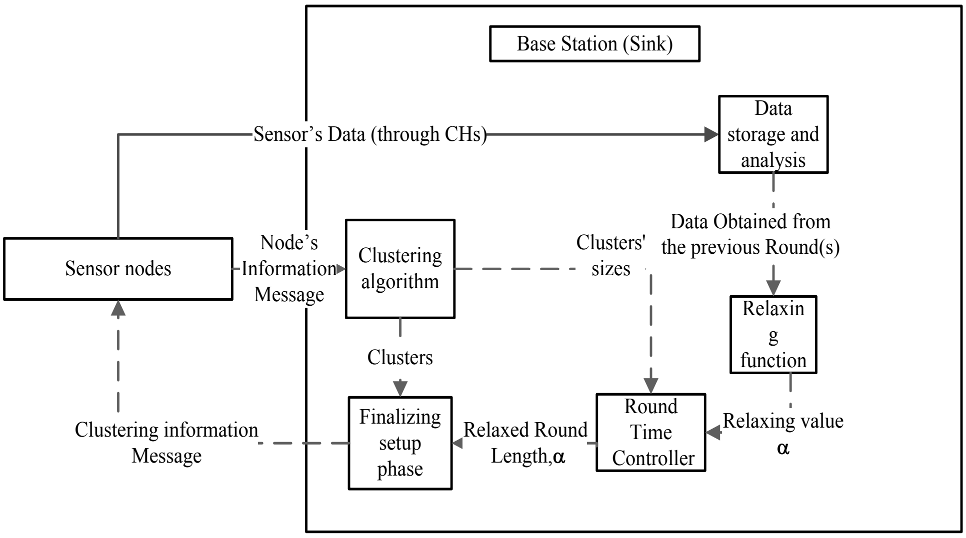

Figure 5.3 the protocol operations, the dotted arrows represent the flow control messages in the setup phase, and the arrows represent the data transfer during the operational phase.

This protocol enables the BS to control nodes' sleeping periods and hence the amount of data delivered over time. RF is implemented to define the relaxing value α to ensure that all nodes will send the required amount of data during the specified round.

As mentioned in previous chapters, the clustering algorithm partitions the network into a desired number of clusters, and these clusters are generally varied in size; therefore each cluster has its own aggregation delay because the aggregation delay depends on frame length. At a minimum, the smallest cluster size has the minimum frame length. And hence during any time period (*t*), different clusters may perform different number of frames, therefore the amount of data delivered (*D*) over time (*t*) is dependent on the number of completed frames by all clusters during *t*.

$$D = \sum_{i=1}^{k} \sum_{j=1}^{li} f_{ij} \tag{5.1}$$

Where k is the number of clusters, l_i is the number of frames performed by the cluster i, and f_{ij} is the number data signals represented by the aggregated data message of cluster i. Therefore, for example, at a certain round, the BS may decide that the amount of data to be sent over time should be maximised, so it reduces the relaxing value α, and as a consequence sensor nodes will dynamically adapt to this change and calculate their sleeping period length and schedule their active period accordingly.

5.3.1 The Setup Phase Functions

The system lifetime of H-RC is similar to MIN-RC, where the network life time is broken down into a set of rounds. Nodes start each round by sending their information to the BS, which is required by the clustering algorithm (nodeid, location, current energy level), and then wait for the clustering information message.
Once the BS has received all nodes' information, then it performs a set of functions (the Clustering Function, the Round-time controller and the Relaxing Function (RF) in order to cluster the network and identify the length of the operational phase of the current round. The details of these functions are:

Clustering Function after receiving nodes' information, the BS then elects a set of eligible nodes to act as cluster heads for the current round. A node is eligible if its current residual energy is greater than the average energy of all live nodes. When the eligible node set is defined, the BS performs the clustering algorithm as in LEACH-C to partition the network into the desired number of clusters. The output of this function is the set of clusters with a cluster head for each cluster. After the network is clustered, the length of the current round is computed by the round time controller, in this case, the MIN-RC.

Round-Time Controller is concerned with identifying the length of the current round ($T_{current}$). The implementation of this function follows the principle of MIN-RC as illustrated in section 3.3, where the clusters' sizes are used as input parameters in order to identify the length of the current round.

Relaxing Function (RF): after that, the relaxing function is executed to compute the minimum aggregation delay level for the current round, and the resulting relaxing value α depends on the implementation of the RF. Then the relaxed round length can be computed as follows:

$$T_{relaxed} = \propto * \ T_{current} \quad (5.2)$$

Finally, the BS creates and broadcasts the clustering information message that contains:

- The cluster head of each node, including the cluster head itself, so that each node can determine its cluster head, and its time slot σ in the transmission schedule.
- The relaxed round length ($T_{relaxed}$): so that all nodes can identify the length of the operational phase, as well as schedule the setup phase for the next round.
- The relaxing value α, so that each node can use α in addition to its time slot σ and $T_{relaxed}$ to schedule its active periods to send its data to the CH.

By receiving the clustering information message, each node can determine its cluster head, operational phase length and relaxing value α, and without loss of generality, each node can calculate its modified slot σ_m to schedule its sleeping periods as follows:

$$\sigma_m = \alpha * \sigma \tag{5.3}$$

The node will utilise only the original slot σ for sending its data to the CH, while the other $(\alpha - 1)$ slots, will be free.

Operational Phase: the operational phase of H-RC, where each node senses its surrounding environment consciously, and adopts its active slot to send its data to the cluster CH. The cluster head in turn aggregates and fuses the received data.

5.4 Simulation and Results

To evaluate the effectiveness of the relaxed round length on the overall performance of the network, different simulation experiments have been designed in order to show how the relaxed round can affect network performance. First, the H-RC protocol was simulated using fixed values for the relaxing the value of α. Secondly, to study the system performance having variable relaxed rounds for the different aggregation delay patterns, a randomized selection method was used to select the relaxing the value of α; for each round, a random value has been chosen for α. Thus, each round may have a different relaxing value and therefore different data rate.

5.4.1 Simulation of H-RC using Fixed Relaxing Value

Recall from Chapter 3 that MIN-RC was used to reduce the energy waste for small clusters or caused by the CH death during the round, and this improved the network's performance by increasing the total amount of the delivered data compared to LEAH-C.

Before looking at variable relaxed values, it would be useful to examine the performance of H-RC in order to investigate the network performance having fixed values for α. Therefore, the first experiment was designed based on having a fixed value of $\alpha=2$.

Figure 5.4 plots the network lifetime. From this figure it is possible to clearly notice the effect of the relaxed round time on the number of nodes alive over time, and the significant improvement of the network life time using the relaxed round length. For further illustration, the effect of the relaxed rounds can be seen in table 5.1 by comparing the network life time for both protocols using different lifetime metrics- the time when the first node dies (1^{st}ND), the time when half of the nodes die (HND) and the time when the last node dies (LND).

From figures 5.5, 5.6, the curve for MIN-RC almost coincides with the one for H-RC, and it is observed that for some rounds there is a difference in the number of delivered messages. This is due to the original round length being generated by the round time controller that depends on the minimum cluster, which can vary for different simulations. Obviously, this is usually foreseen in such dynamic clustering protocols, although there is a noticeable difference in the amount of delivered data per round; however, the difference in the total amount of data delivered is marginal, and both MIN-RC and H-RC can approximately deliver the same amount of data, this can clearly be seen in figure 5.6.

Figure 5.7 illustrates the influence of relaxed rounds over the number of data messages sent by the network over time. As expected, it is possible to see from this figure the decrease in the number of messages. This is due to stretching of the frame time length by slot scaling, which adjusts the traffic load over time. For further illustration, it can be observed that, for example, at round 1 the amount of data delivered by H-RC is 2299 and by MIN-RC is 2283, while the average number of messages per second under MIN-RC is 152 and for HR-C is 77, and α is equal to 2. From this figure, it can be seen that for the last rounds the number of messages per second achieved by H-RC is higher than that achieved by MIN-RC, which seems to be unreasonable; however, in such a dynamic system the cluster formation can vary for different simulation runs, thus the system behaviour can vary accordingly. This means that the round length and the cluster sizes would vary, and therefore the system's performance will vary accordingly.

Table 5.1 the percentage of improvements of H-RC with α=2 compared to MIN-RC using different evaluation metrics.

	H-RC	**MIN-RC**	**LEACH-C**	**Improvement over MIN-RC**	**Improvement over LEACH-C**
1st ND	644	319	350	200%	184%
HND	865	449	502	193%	172%
LND	1014	513	551	198%	184%

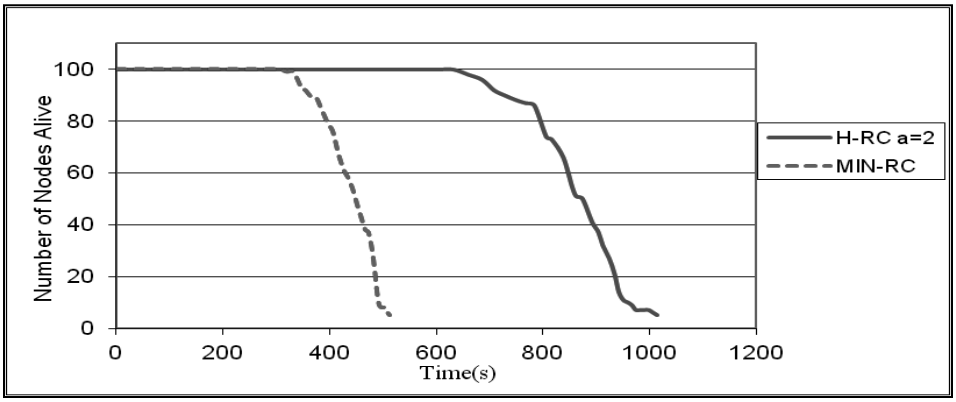

Figure 5.4 the number of nodes alive over time in seconds, for the relaxing value α=2 and MIN-RC

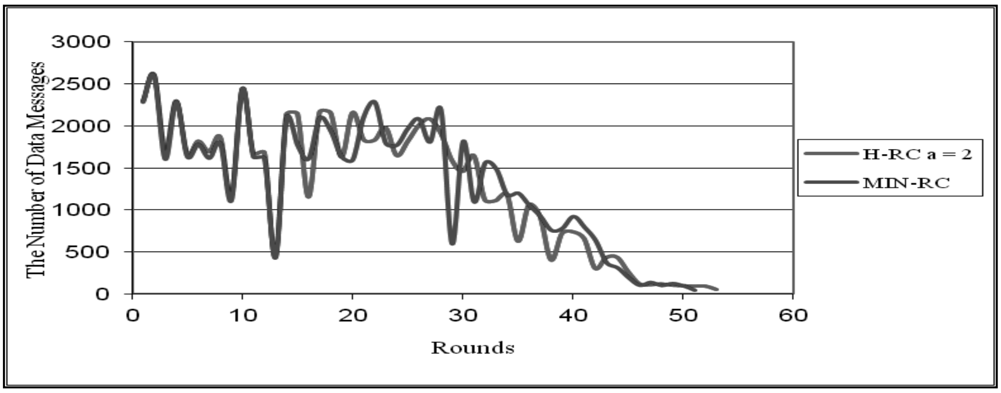

Figure 5.5 the number of the delivered data messages per round, for the relaxing value α=2 and MIN-RC

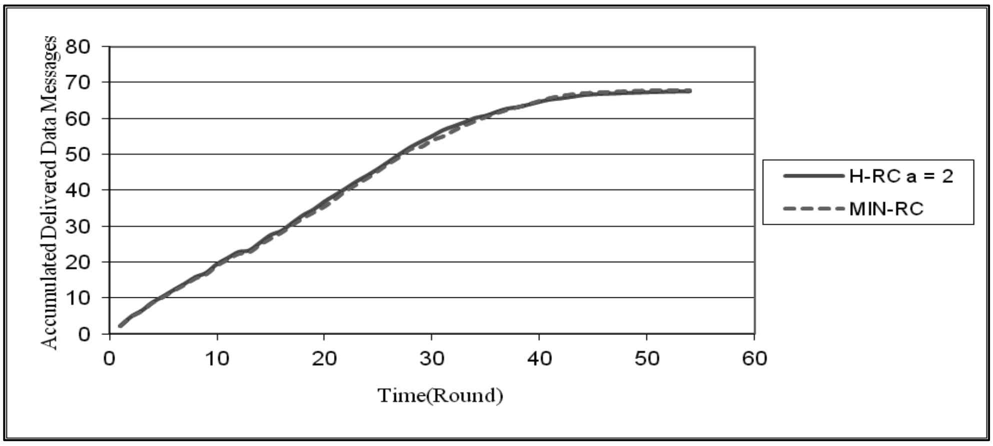

Figure 5.6 the accumulated number of the delivered data over time in rounds, using the relaxing value α=2 and MIN-RC

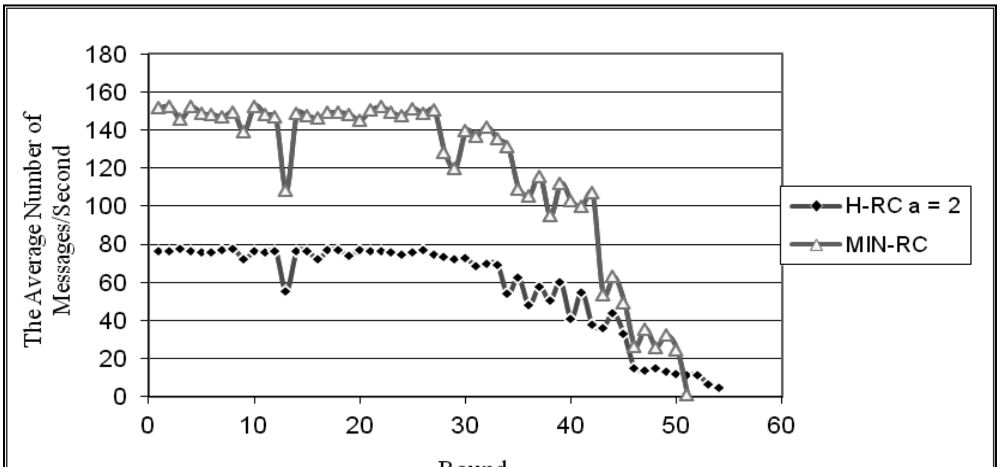

Figure 5.7 the average number of data messages for a unit of time (second), for the relaxing value α=2 and MIN-RC.

5.4.2 Simulation of H-RC using Variable Relaxing Values

Finally, the second experiment was designed to investigate the effect of varying values of α. From this experiment, the aim is to study the performance of the proposed protocol under variable levels of aggregation delay requirements during the network life time.

For this experiment, although the relaxing function would be application specific, for the purpose of evaluation, a relaxing function has been designed based on randomness. It has been assumed that the relaxing function will generate a random value for α between 1...2.

With this implementation of the relaxing function, the values of α is a seemingly random series of real numbers between 1 and 2, where variance of the data rate per round is marginal. Figure 5.8 and figure 5.9 show an example of a single run for the H-RC. Figure 5.8 plots the original and the relaxed round length, and from this figure it is possible to see, for example, for rounds 1 and 3 that both curves approximately coincide. This is because the generated values from the relaxing functions are 1.0423 1.0466 respectively, therefore with these small values for α the difference between the original and the relaxed round length will be very small; while at rounds 10 and 12 the generated values for α are 1.796 1.617, therefore the difference between the original and the relaxed round length is quite high.

Figure 5.9 plots the average number of messages sent per second, and from this figure it can be observed that when the value of α is too small, both MIN-RC and H-RC deliver approximately the same number of messages. For example, at round 3, 13 where the values of α are 1.0466, 1.0346 respectively, it can be seen that the difference in the number of delivered messages is very small, and both curves of MIN-RC and H-RC with variable α coincide; while this difference in the number of delivered messages increases as the value of α increases, for example at round 11 and 23 where the value of α is 1.922.

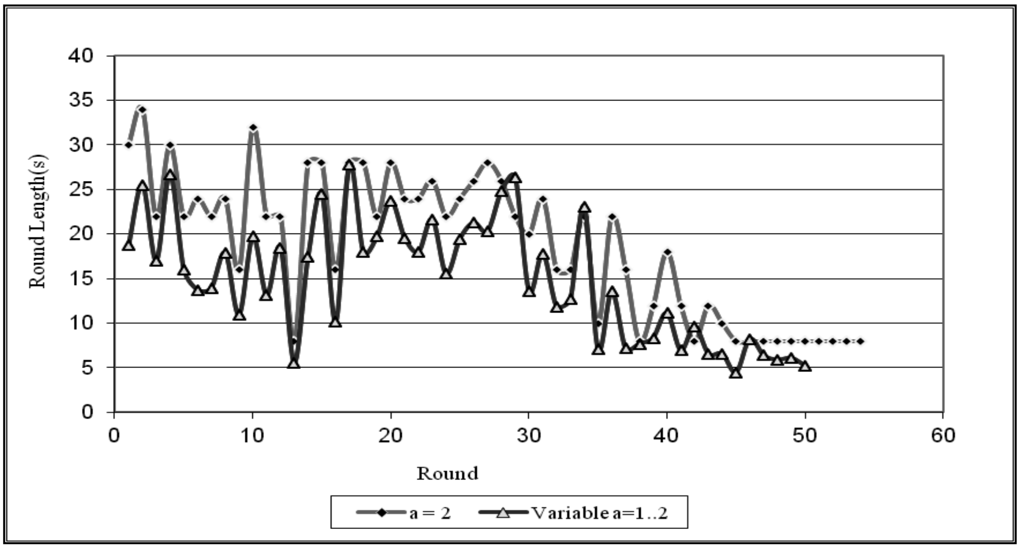

Figure 5.8 the round length, with α=2, and with random values for α between 1 and 2.

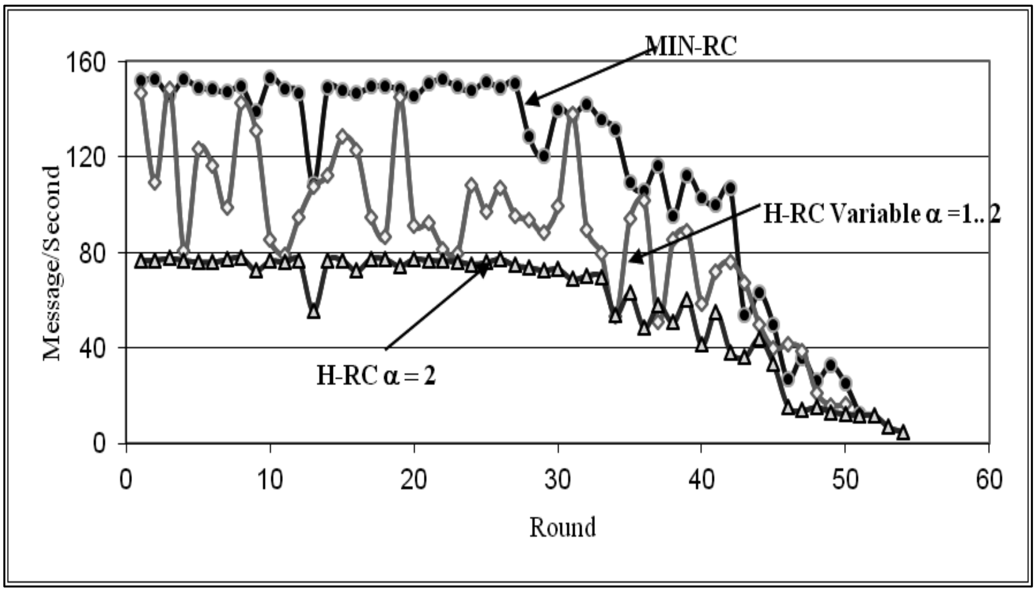

Figure 5.9 the average number of messages with the round number, for both fixed and variable values of α.

Typically, the randomised nature of the values generated by the relaxing function will generate different values for α for each simulation run; therefore, to study the performance of the protocol in this context, this experiment has been repeated five times. Then, the average for these trials was computed to investigate the protocol's effectiveness having variable relaxing values.

The figures plotted below compare H-RC having variable relaxing values to both H-RC having fixed relaxing value, that is α=2 and MIN-RC.

Figure 5.10 shows the total number of data messages sent over round time, and figure 5.11 plots the average number of messages sent per second. From both figures it can be noted that MIN-RC has the highest data rate compared to both fixed and variable relaxing values. It can also be noted that under MIN-RC and H-RC with α=2 the shifting in the number of delivered messages per second for adjacent rounds, for the most of network lifetime is negligible. However, under H-RC with variable values of α, one can observe that this shifting is evident. This reflects the effect of the random generated values for α. In general, the round length increases in case of the large values of α. Accordingly, the number of data messages received at the BS per second decreases, and from this result it can be assured that the H-RC is more flexible than the traditional protocols and has the ability to support various application requirements by adopting different aggregation delay levels.

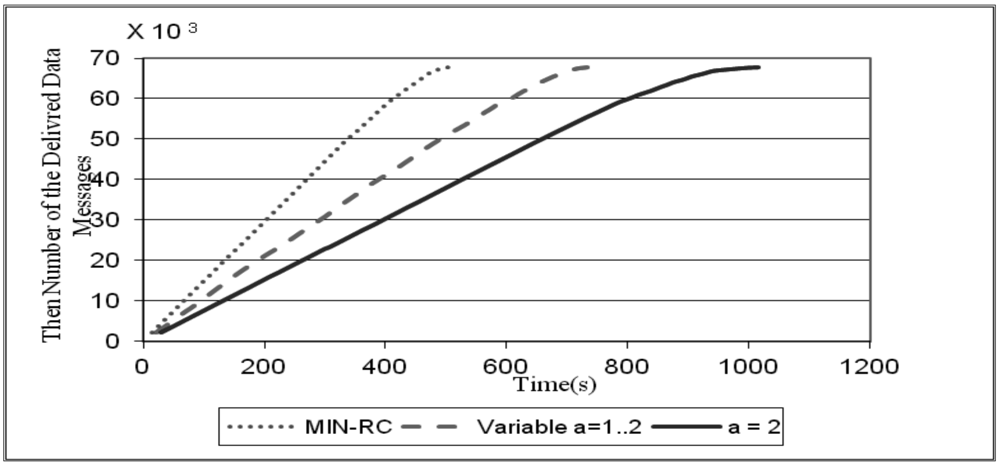

Figure 5.10 the total number of received data messages over time in seconds, for both fixed and variable values of α.

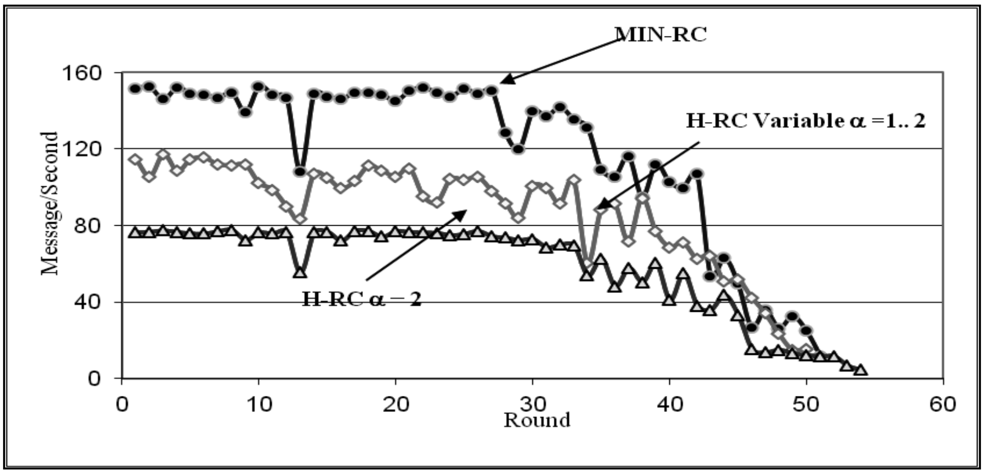

Figure 5.11 the average number of messages with the round number for both fixed and variable values of α.

To sum up the ordinary behaviour, when values draw near 1, the network performance will be more efficient in terms of the amount of data delivered over time, and thus can give a clearer image. In contrast, the amount of data drops as the value of α increases, so that nodes can acquire longer sleeping times, saving more energy, at the same time, the energy dissipation per round is minimised as nodes turn off their radios for a longer time and save their battery power. This can be seen from figure 5.12 which plots the energy consumed per round. From this figure, it can be observed how the amount of energy consumed per round varies according to the variance of α , so it can be concluded that the use of a long time frame shows potential improvement for the network lifetime.

The effect of the variable values of α on the network life time is illustrated in figure 5.13. This figure plots the number of nodes alive during the simulation time. The results shows that under H-RC for both fixed and variable relaxing values, sensor nodes have a longer life time compared to MIN-RC , and the percentage of the network lifetime improvements of H-RC is further illustrated in table 5.2. From these results, it can be said that with variable relaxing values, the network extends its lifetime using different lifetime evaluation metrics, for the time when the first node dies (FND), the time when half of the nodes die (HND) and the time when the last node dies (LND).

Table 5.2: the percentage of improvements of H-RC compared to MIN-RC using different evaluation metrics

	MIN-RC	H-RC α=2		H-RC variable α	
			Improvement		Improvement
1st ND	319	644	200%	482.6	152%
HND	449	865	193%	641	146%
LND	513	1014	198%	754.2	146%

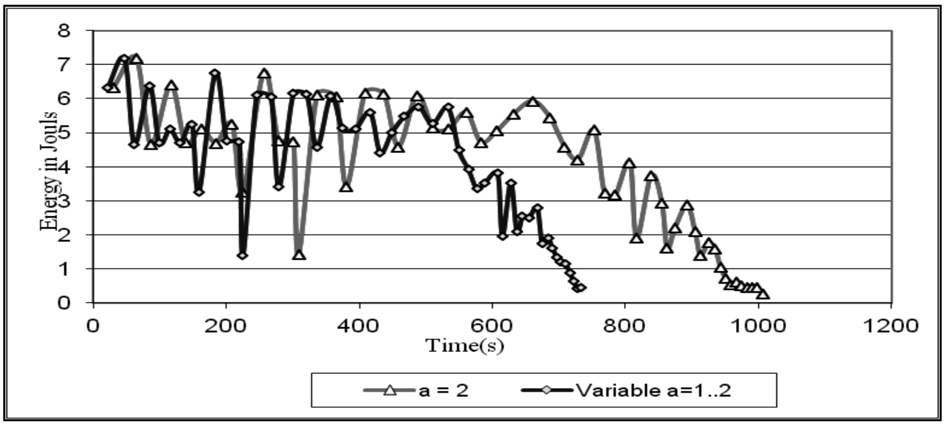

Figure 5.12 the energy consumed in joules per round over simulation time, for both fixed and variable values of α.

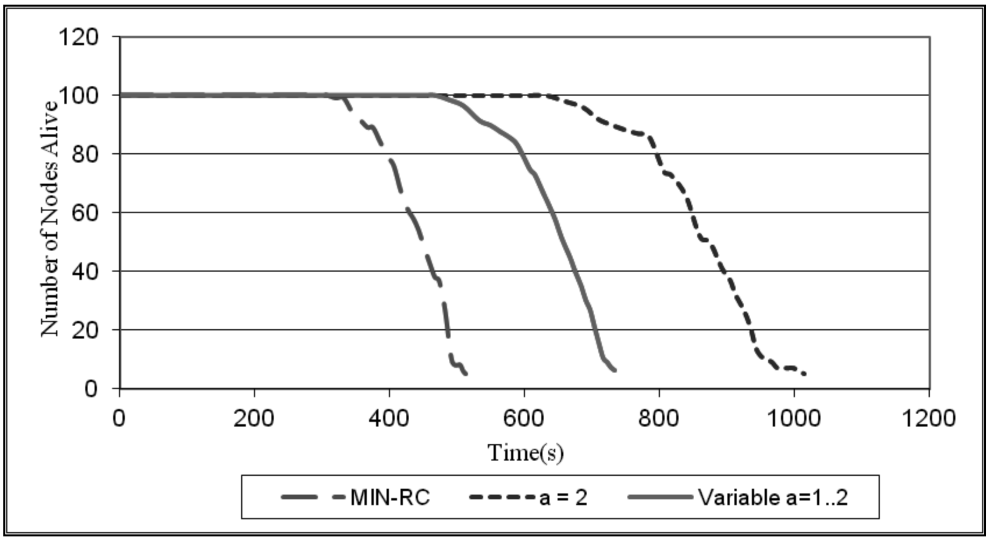

Figure 5.13 The number of nodes alive over time, compares MIN-RC with a fixed value for α=2, and variable value of α which randomly select in the range 1 to 2

5.5 Summary

In this chapter, a novel general approach to energy management in cluster-based wireless sensor networks has been presented.

If multiple aggregation delay levels are considered, the proposed scheme can boost the performance of the network in terms of extending the network's life. H-RC trades between the numbers of delivered data messages over time, and network longevity tolerates different relaxed round lengths for different aggregating delay levels.

The use of relaxed rounds has been presented, with MIN-RC considered as the round-time controller scheme. In principle, nothing prevents applying relaxed rounds on top of any other clustering scheme. Using a joint scheme of relaxed round controller in addition to MIN-RC can help to prolong the network's life time as well as increase the total amount of data delivered compared to the traditional LEACH-C protocol.

The H-RC enhances network flexibility. The network is able to adjust the round length by changing the aggregation delay level that assigns different values for α. The large values for α allow a sensor node to acquire a longer sleeping time, therefore saving energy, while small values makes the sensor carry out more frames and send more data during the same round thus improving the quality of the obtained measures.

It has been shown through simulation that H-RC can be considered to be a general energy management strategy for cluster-based wireless sensor networks. One of its advantages is its suitability for different applications' requirements, as well as different aggregation delay levels for the same application. In these simulations, the effect of using fixed relaxing value, α=2 has been investigated, along with varying values of α in the range 1...2. Further simulations results will be discussed later on in chapter 6.

Although the proposed protocol has shown significant improvement in the overall performance, the implementation of the relaxing function, and how to trade between both the amount of data and the network longevity, still leaves the question open, and its answer will be an application specific design issue, for example applications requiring periodic sampling, so the sample rate can be adjusted according to the frame length in order to save more energy.

CHAPTER 6

Critical Review

6.1 Introduction

In this chapter, a critical review of the proposed schemes described in this thesis will be provided. It will state the advantages and limitations of these schemes, as well the potential improvements.

6.2 The Round Time Controllers

Basically, two methods, namely MIN-RC and VAR-RC, have been proposed to control the rounds' operational phase to improve network performance by reducing the effect of having a fixed round length. They are distinguished by the total amount of data delivered and the acceptable delay in the data delivery.

The **MIN-RC** scheme provides a dynamically quick recovery from uneven clusters resulting from dynamic clustering, since it computes the round length with respect to the minimum size cluster. It also has the potential advantage of reducing the effect of the CH's death during the round, since the resulting round length will be smaller than the original fixed length round.

MIN-RC uses small round length, because the smallest cluster size is used to determine the round's length. The use of small round length has several advantages:

- First, the use of small length rounds reduces the effect of the CH’s death throughout, as in line with the cluster head's death, nodes belonging to this cluster will keep sending their readings to the cluster CH wasting energy because nodes would have no idea about the head’s death; therefore, minimising the round length has the potential to reduce the resultant energy waste, this can be clearly seen from figure 6.1, which compares the total amount of energy wasted results from the death of the cluster head during the round.
- The second advantage is that the network can quickly recover from unbalanced clustering. In such situations, with different cluster sizes, a cluster with fewer members would have a small length frame; therefore, the number of completed frames is magnified. In this way, the head needs to communicate more frequently with the BS, using mp to avoid multipath fading, and therefore consuming more energy to send data messages that represent fewer nodes' readings.
- Although the MIN-RC shows a significant improvement in the total number of data signals received at the BS, nodes will perform more rounds compared to LEACH-C. As mentioned earlier, each round has a setup phase that requires nodes to send their information to the BS, and receive the clustering information message. When a node sends its information to the BS, this requires more energy to avoid multipath fading; therefore, having more rounds will introduce an extra setup cost. In particular, the higher the number of rounds, that is the higher setup signalling, the greater the energy cost; however, this extra cost is

insignificant compared to the significant improvements in total energy utilization, figure 6.2 compares the setup energy cost of MIN-RC to LEACH-C, from these figures we can see how the extra setup messages has not a significant effect on overall performance and the extra setup constitutes less than 2% of the energy saved by MIN-RC.

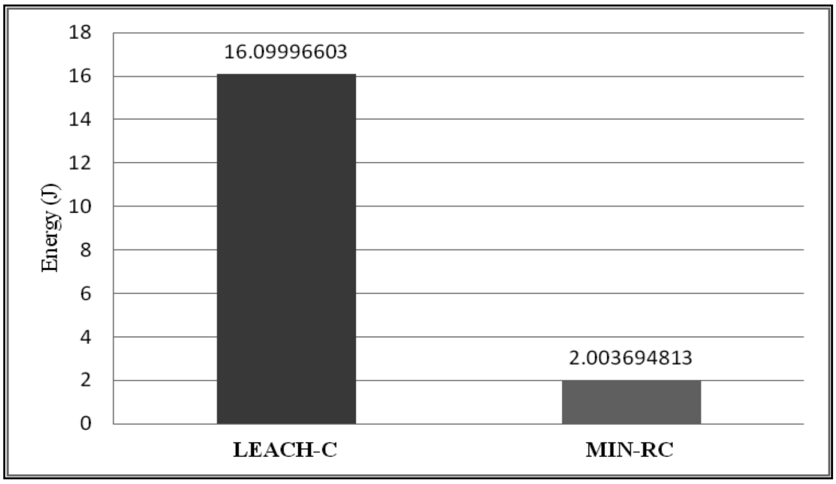

Figure 6.1 the total of the energy waste results from the death of the CH during the round.

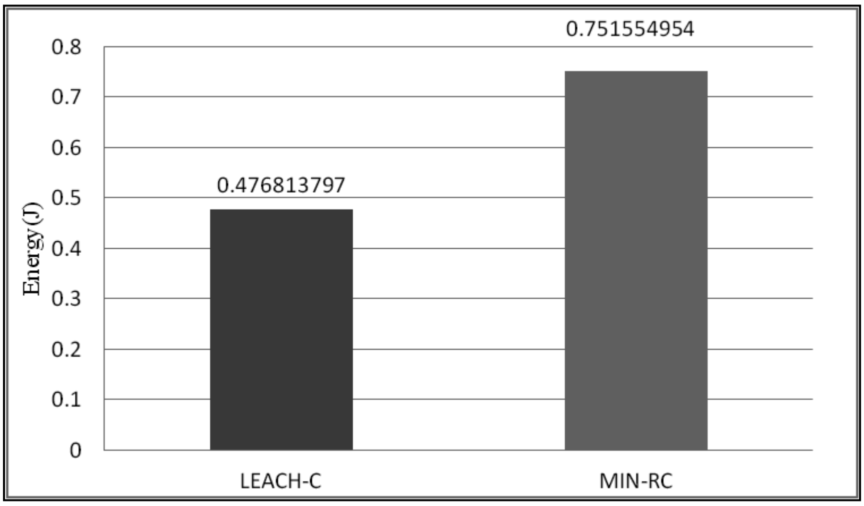

Figure 6.2 the setup energy cost for both MIN-RC and LEACH-C.

The **VAR-RC** has been designed from the desire to control the number of data signals. In this way, the smaller sized cluster means that round time length is relaxed.

The variable round time controller balances the number of frames performed during the round time, and in this way all nodes will send the same number of data signals, as well all heads sending the same number of aggregated data signals. Thus, regardless of the cluster size, the BS will obtain the nodes' readings with approximately the same aggregation delay, where the aggregation delay is bound to the maximum frame length- that is, the frame length of the largest cluster size.

In general, the round length increases subject to the largest-sized cluster. Accordingly, when the resulting maximum cluster size is very large, the aggregation delay and the number of data signals received over time are magnified. Hence, the aggregation delay increases as the frame length increases, so the problem here is that in time, for sensitive applications, this may lead to losing important readings. Another shortcoming of very large cluster size is that the CH frame cost is increased as the number of members is increased, as shown by equation 3. Consequently, the head of this cluster will consume more energy; therefore the VAR-RC requires more refinement in order to solve this problem. An optimisation method is needed to balance between network longevity and the maximum aggregating delay. Another alternative solution to this problem is to add an application specific threshold to specify the maximum aggregation delay, and therefore the maximum round length can be identified accordingly.

6.3 Load Sharing Technique

The CCH, presented in chapter 4, provides a mechanism for load sharing in order to reduce the effect of unfairness of load distribution, thereby balancing the energy consumption among nodes.

- Depending on the current clusters' formation the BS can determine whether the cluster would have an alternant CH or not, the cluster will have a CCH if the conditions below are satisfied:
    1. The CH is expected to consume more energy than average.
    2. The existence of a cluster member that satisfies the optimisation function, as mentioned in chapter 4, the CCH is determined by employing one of the selection CCH selection schemes, and where two selection schemes have been proposed to select the CCH, the minimum cost and maximum energy.

Having an alternate Cluster Head can improve the adaptation to the changing network and provide a way out of the CH's death during the round; consequently reducing the resultant energy waste from the CH's death.

Although having an alternate cluster head has the advantage of improving the network's performance, electing the CCH that is the node to operate as a CH is a thorny task, because an inappropriate selection may result in poor performance. For example, electing a node with low energy level can result in fast depletion of their energy source, and subsequently faster node death. Also, the location of the CCH will increase the intra-cluster communication overhead, because the intra-cluster communication is magnified $\sum_{i=1}^{m} d_{i\_toCCH}^{2}$, m denotes the number of member in the cluster, d_{i_toCCH} distance from node i to the CCH.

From the above mentioned concerns, two optimisation schemes have been used to elect the CCH. The first one is concerned with the intra-cluster communication, where the member with CCH minimum intra cluster communication energy cost is as CCH chosen, while the second one selects the member that has the maximum energy level. In addition, both the election schemes must assure that at the end of the round the energy level of the CCH must not fall below the energy level of the original CH.

Although the CCH has the potential to improve the network's performance, it has other implementation problems that can affect network performance. This is due to determining the amount of load that the CCH will carry out, thus for the purpose of evaluation, the CCH has been tested through intensive simulations using limited but illustrative values for load percentages (0.1, 0.2, 0.3, 0.4 and 0.5).

The network designer needs to be aware of this feature of the CCH protocol when the network is designed, recall from tables 4.1 - 4.3, the value of p shows a greater impact on network performance. As to which values of p are best, in fact there is no simple answer. The amount of shared load must be optimised in sight of the application requirements.

Therefore, this increases the need for further optimisations to identify the percentage of the shared load. Furthermore, a fixed value for p was used, which raises two other questions:

- What is the effect of having a variable shared load for different rounds?
- Can assigning different values of p to different clusters during the same round affect the network's performance?

Thus, defining the amount of the shared load is a future research optimisation question, and clearly, due to the application's requirement concerns, answering these questions will form part of our future research.

6.4 Hybrid Protocol for Various Application Requirements

Basically, as mentioned in chapter 5, the current concern is to design a cluster-based routing protocol that is suitable for different data models as well as supporting various aggregation delay level requirements during the network's lifetime.

The H-RC protocol aims to spread the data transmission over a wider round length to maximise the node's sleeping period and reduce the energy consumption over a specific operational period.

The H-RC protocol's main features are as follows:

- The value of α can be determined in sight of the time critical data requirements so that smaller values for α make this scheme suitable for time sensitive applications.
- The relaxing value α can be varied, depending on the current state of the network and the previously delivered data and the application requirements. This gives the protocol the advantage of adapting to the network's status and supporting various application requirements.
- With small values of α, nodes will send more data over a specific period of time, which means that a more accurate picture of the monitored phenomena will be obtained, of course, with an increase in energy expenditure. Thus, controlling the trade-off between energy efficiency and data accuracy will depend on the implementation of the RF, so it is the network designer's prerogative to identify the proper implementation of the RF in sight of the application requirements.
- The relaxed round can be quite effective in situations where the required amount of data varies over time; that is, different aggregation delay levels may occur.
- The relaxed round scheme is independent of any clustering algorithm.

The principal disadvantage is that H-RC tolerates some latency. Since sensors may have long sleep periods, the sensor's sleeps periods are determined by the relaxing value α as well the length of the TDMA schedule; therefore potential loss of important data may result. This is because, for example, assuming that a sensor node adopts a long sleeping period and a critical event occurs in this node's sensing range, the node will wait for its next active slot to report this event. Also, the CH will wait until all nodes in the cluster to send their data before sending the aggregated data message to the BS, therefore the network will fail to report this critical event. Moreover, depending on the extent to which this event is critical, this failure may result in it losing the purpose of application's design and this may lead to disastrous results.

Therefore, such unpredictable situations require a dynamic response, and this will be part of future work to solve the above mentioned problem and enhance the protocol's flexibility. Hence, with a long frame, that is $\alpha >= 2$, there will be a free slot so that it can be used by any cluster member to report its critical data to the CH. On the other hand, the CH can decide whether to immediately aggregate and send the currently available data, or wait till the frame ends (collecting all member's data), and this decision can be based on the typical deployment of the sensor nodes over the sensing area. Where sensors are densely deployed, in such situations where the deployment is dense enough, the CH can receive similar data signals from other nodes in the cluster; therefore, depending on the how critical the event is and how many sensors have reported this event, the CH can make the proper decision.

To further investigate the suitability of the protocol for different application requirements, different simulations have been conducted to study the protocol's efficiency using constant and variable values for α. In these simulation experiments, H-RC has been tested using a set of large constant values for α (5, 10, 20), and for variable aggregation delay requirements. For the same application, the values of α are chosen randomly between 1and 5.

From figure 6.3, which plots the number of nodes alive over time, it is observed that nodes would live for longer time as the value of α increase. However, the round length under H–RC is quite long, a magnitude of α, which means the number of delivered data messages per second will decrease accordingly. This can clearly be seen from figure 6.4

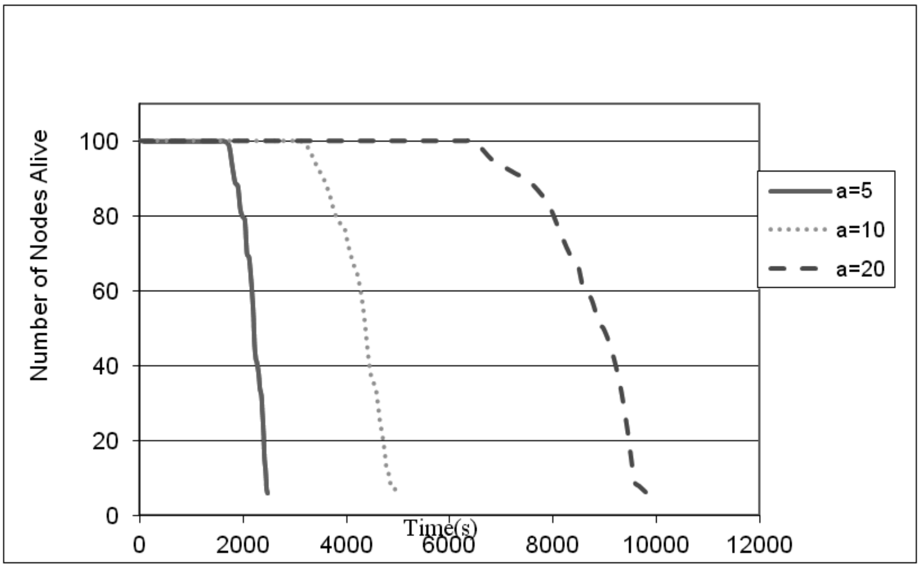

Figure 6.3 the number of nodes alive over time in seconds, for the relaxing value α =5, 10 and 20

From these results, the suitability of H-RC for different application data models has been proven, and it has the ability to adapt to various aggregation delays in line with the application's QoS requirements. For a specific application of QoS requirements, these requirements should be reflected in the design of the relaxing function, so that the value of α can be calculated to achieve the desired number of data messages, considering the resulting clusters for the current round.

The H-RC enhances the network's flexibility using relaxed rounds. Through this controlling scheme, the BS is able to adjust the round length, increasing the aggregation delay, while the network still delivers the same amount of data during the round as MIN-RC.

From these figures, it is observed that there is no significant decrease in the total amount of data received at the BS, while the improvement in network lifetime is obvious.

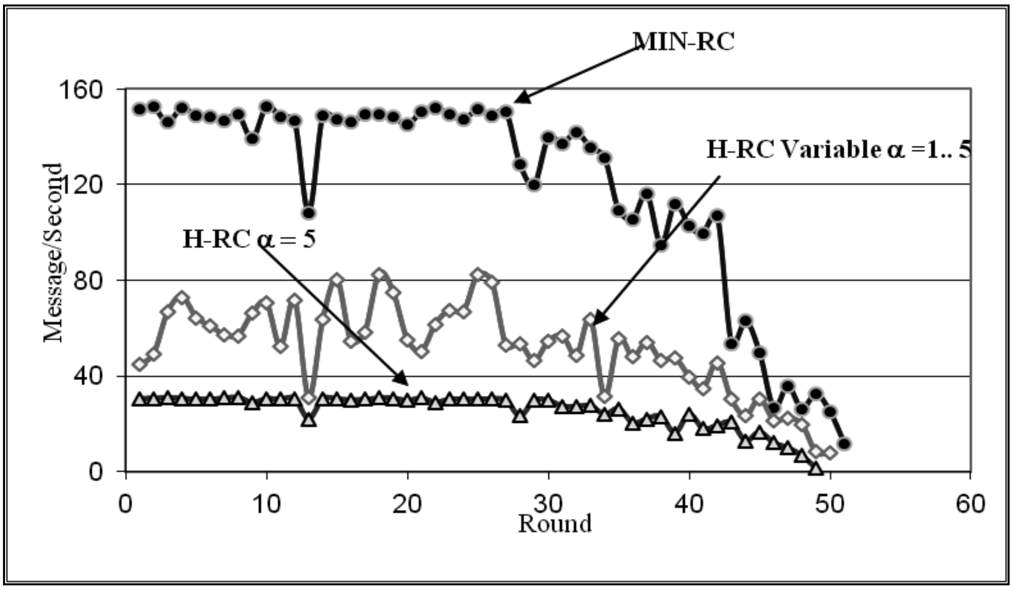

Figure 6.4 the average number of data messages for a unit of time (second) ,for the relaxing value α=5 , and the value of α randomly selected between 1 to 5

To sum up, the main advantage of H-RC is that, with this controlling scheme, it can support different application requirements. In order to work to support various application requirements, the relaxing value parameter α is used to identify the aggregation delay that the BS attempts to achieve, and the RF automatically adjusts the relaxing value α according to the required delay level, while considering the current state of the network. Therefore, the value of α is used to increase or decrease the aggregation delay, and accordingly, the round length. In this way, the total amount of the delivered data signals will vary accordingly.

Providing a clearer image of the monitored phenomena and adopting long sleeping periods to save energy work in opposite directions. With too short sleeping periods, for the data transmission, nodes are required to turn on their radios more frequently to report their readings, and thus consume more energy which results in faster depletion of their energy source, and consequently speeds up the node's death. With longer sleeping periods, losing important data may result, or poor images of the monitored phenomena.

H-RC aims to balance between the above mentioned requirements by limiting the node's active periods, while giving the BS the ability to change network behaviour for a desired aggregation delay level; accordingly, nodes will have a shorter sleeping period.

When clusters are needed, although small sizes result in uneven network partitioning, this may be advantageous, as small sized clusters will have a small frame length, and accordingly smaller aggregation delay compared to large-sized clusters. As a result, the cluster will carry out more frames during a specified time period. In this way, the BS will gain a clearer image of the area covered by this cluster, naturally with its energy expenditure.

CHAPTER 7

Conclusions

In cluster-based WSN research, it is important for the network designers to have a basic understanding of the clustering attributes such as the number of clusters; how frequently clusters are rebuilt; cluster size; number of hops (single hop or multihop), and they must be conscious of energy consumption. Such perceptiveness and awareness promote general discussion about the clustering problems and their potential solutions, and often assist with the available energy being spent in an efficient way that conveys the intended design goals of the WSN application. In this dissertation, the ultimate goal was to design a set of effective energy management schemes to achieve the design goals, lifetime longevity and the desired amount of data delivered.

7.1 Summary of Contributions

In chapter 3, two adaptive techniques have been presented for reducing the effects of fixed-length rounds, so that the round's operational phase can be determined in view of the application's requirements, in addition to the current state of the network. The first scheme is the variable round controller. VAR-RC aims to balance the number of frames that the cluster can carry during the round, thus the round length is computed considering the maximum cluster size, and nodes belonging to small sized clusters adopt longer sleeping periods thereby avoiding frequent transmissions to save energy. The second scheme is the minimum round controller MIN-RC. In this scheme, the round length is reduced, therefore small clusters can avoid sending more frames, as well as it providing faster recovery from the cluster head's death.

In general, a WSN application is obvious clear example of cooperation, where an image of the observed phenomena results from the cooperation of the deployed sensors. Moreover, clustering is a promising method for enhancing the network's efficiency by increasing the cooperation among nodes, although, as a result of this study of the cluster-based WSN, it is assumed that there is still space for more cooperation in cluster-based WSN to achieve potential system performance improvements. With this motivation, the Co-cluster head routing protocol was developed.

The key idea of the assumed cooperation method is that a cluster member can be elected to carry out some of the CH's load. This is because some of the CHs may carry out more frames than others because of uneven clustering, as well it being very common that a CH may die during the operational phase. For these reasons, a CCH can provide a promising way out from such situations.

For the purpose of election of the CCH, selection schemes were applied. The first one selects the node that minimises the intra-cluster communication cost, while the second one selects the nodes that have the maximum energy level, and to minimise the opportunity of faster depletion of the selected node battery, both of the optimisation schemes assure that the residual energy of a node, if selected as a CCH, must not fall below the original CH's residual energy.

Chapter 5 explored the need for a general WSN routing protocol that can adapt to various application requirements. The purpose of the current research is to introduce a potential design for a power management scheme that can provide the key to developing a general routing protocol for WSN that can support various application requirements. The H-RC protocol was developed to support different aggregation delays. The key feature of this protocol is that of using the scaled-round mechanism which provides the WSN application with an advanced energy management mechanism to maintain scaled-frames. Thus, nodes can utilise longer sleeping mode periods to save energy.

Basically, the performance of H-RC has been evaluated where the original rounds are computed based on the principles of the MIN-RC. However, nothing prevents the implementation of the relaxed round scheme on the top of any clustering technique in which the system lifetime is composed of numerous rounds.

7.2 Future work

Although the schemes developed in this dissertation show significant improvements for energy management in WSN, we believe that there is still a room for improvement, and these highlight our future research directions.

The evaluation of the CCH protocol for both selection schemes has been tested using the fixed values of an assigned shared load. This showed that the effect of the death of the CH can be reduced as the amount of the shared load increases. However, this can increase the amount of energy consumed by the CCH, as well the intra-cluster communication cost, therefore a further optimisation is required to choose the optimum value of the shared load, of course taking into consideration the application's requirements.

Another promising solution is that different clusters (CCH) may adopt different shared load percentages.

The H-RC enhances network flexibility. The network is able to adjust the round length, increasing the aggregation delay, and can still deliver the same amount of data during the round as MIN-RC**.** However, in WSN, critical events may occur arbitrarily, so such unpredictable situations require a dynamic response, because with long frames an important reading may be lost, and this could be disastrous. Thus, for a potential improvement, the sensor node could utilise one or more of the free slots to report its data critical measure(s) to the CH; on the other hand, the CH can decide whether to send the currently available data.

Another natural perspective exploits the advantages of all the developed schemes, by designing a configurable scheme, so that it can be the network designer's choice to activate /deactivate or create more schemes.

Finally, the efficiency of our energy management schemes has been evaluated on top of a centralised clustering scheme, although studying the implications of applying these schemes in self-organising methods is a significant direction for future work.

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